Progress on SM Higgs precision calculations

Robert Harlander
RWTH Aachen University

31st Rencontres de Blois
June 2019

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The Standard Model

"Of course, [this] model has too many arbitrary features to be taken seriously."

S. Weinberg '67

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- parity violation
- gauge structure
- hypercharges
- number of generations
- Higgs representation
- y_t=1 vs. y_b = 0.02 vs. y_μ = 0.0006
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… and it's incomplete, of course…

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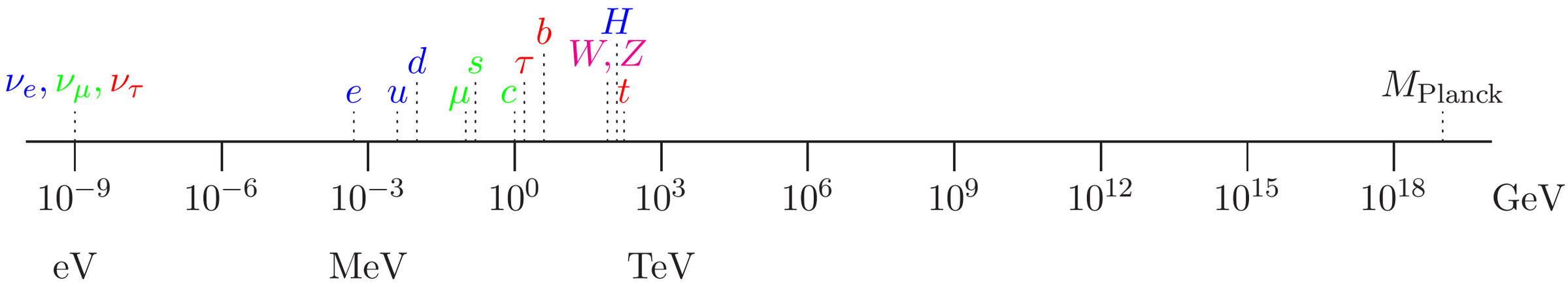

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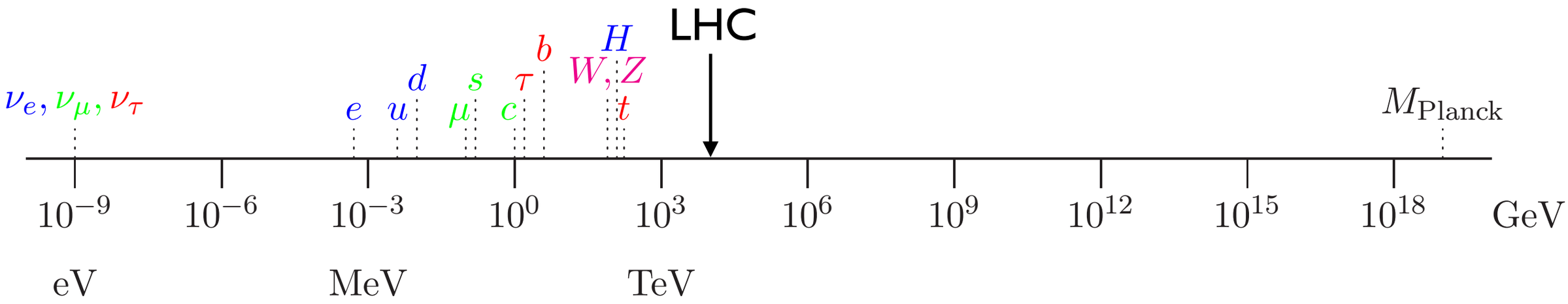

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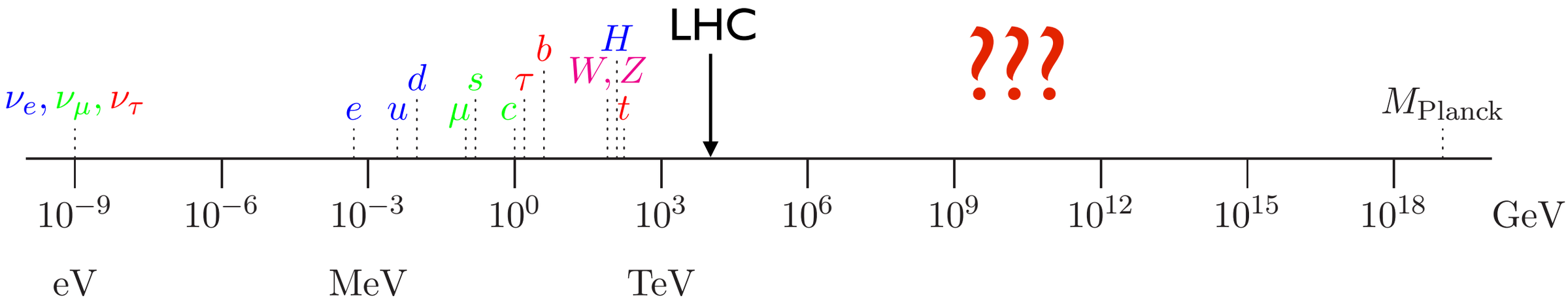

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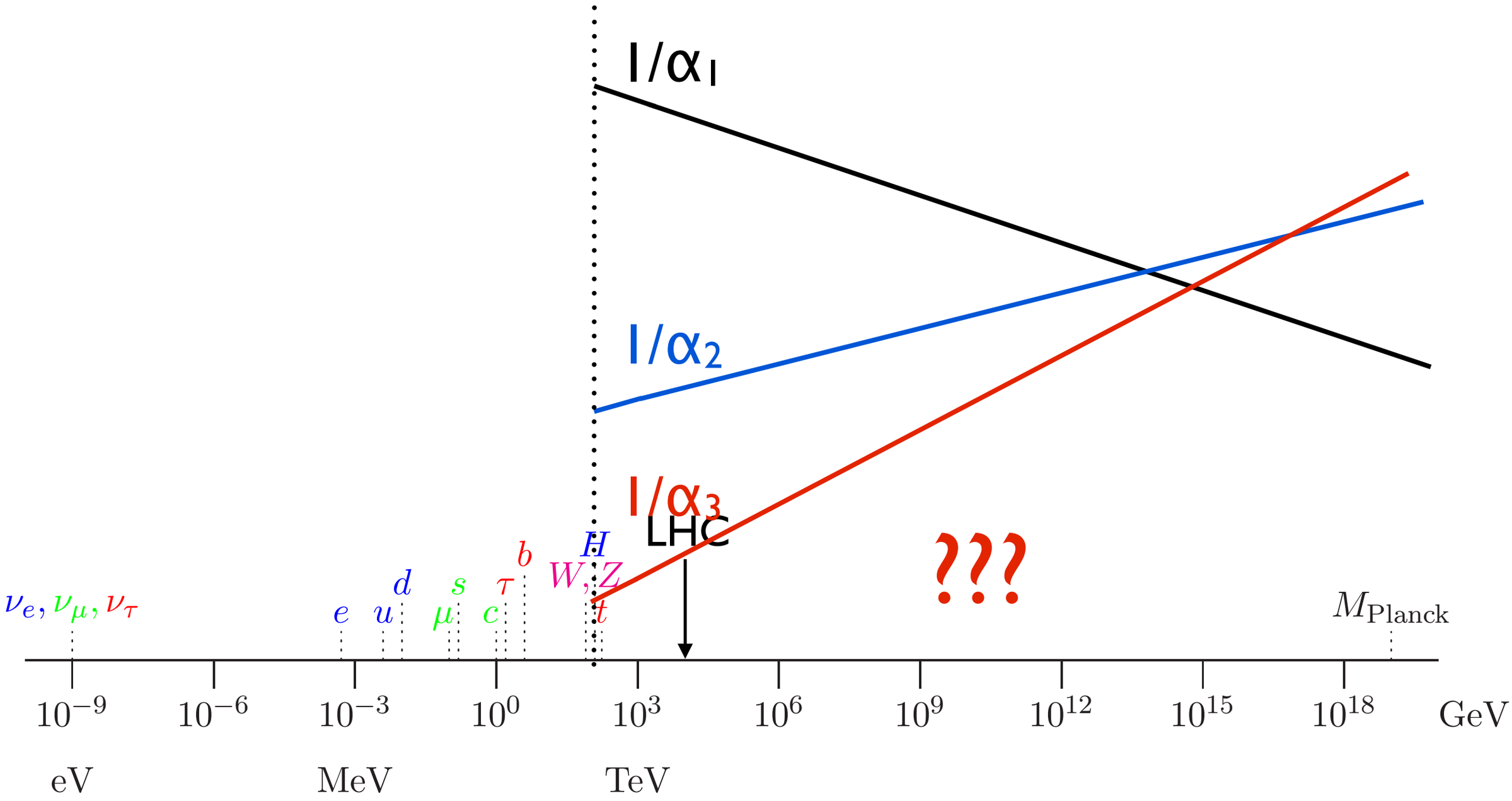

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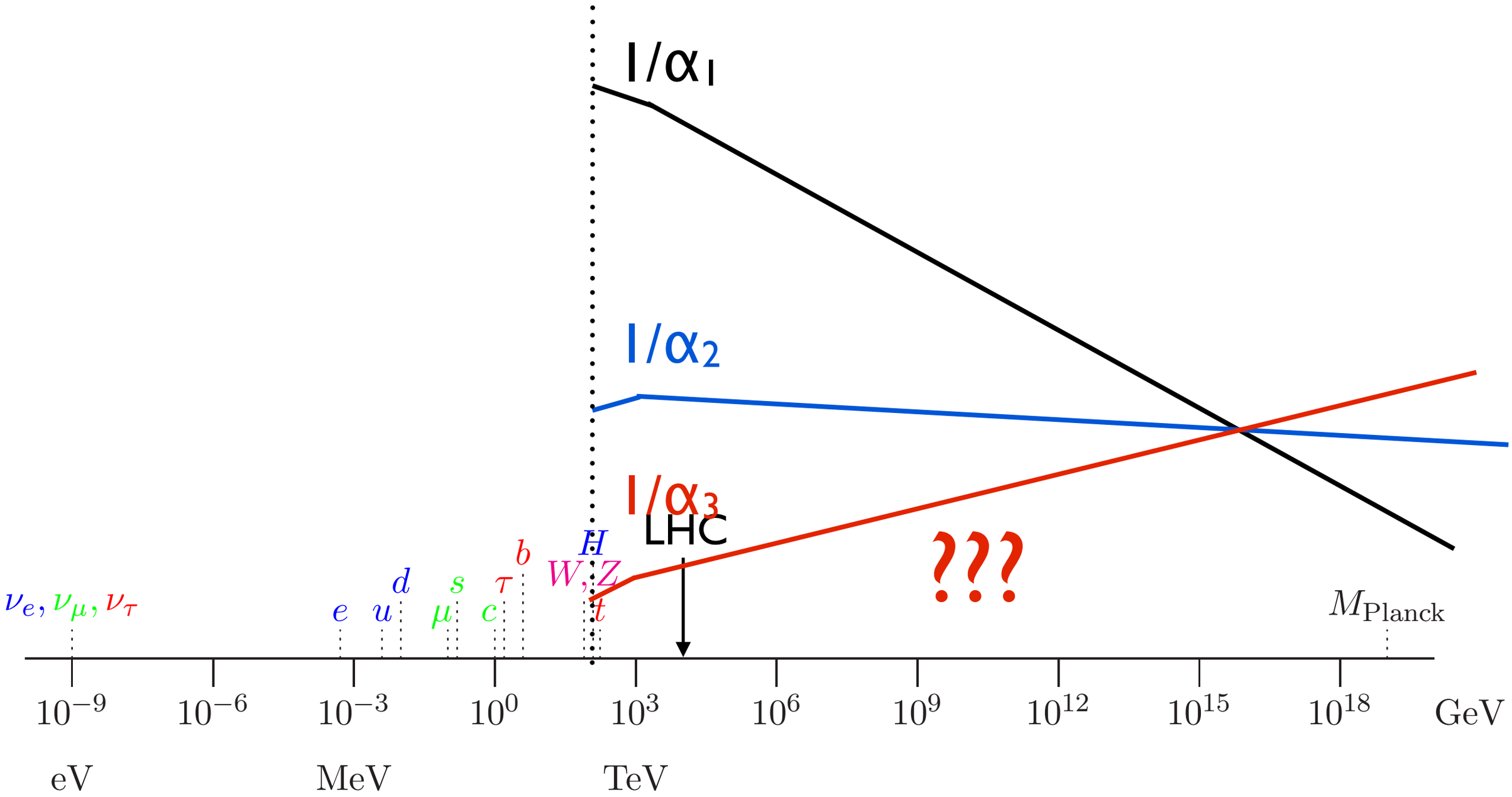

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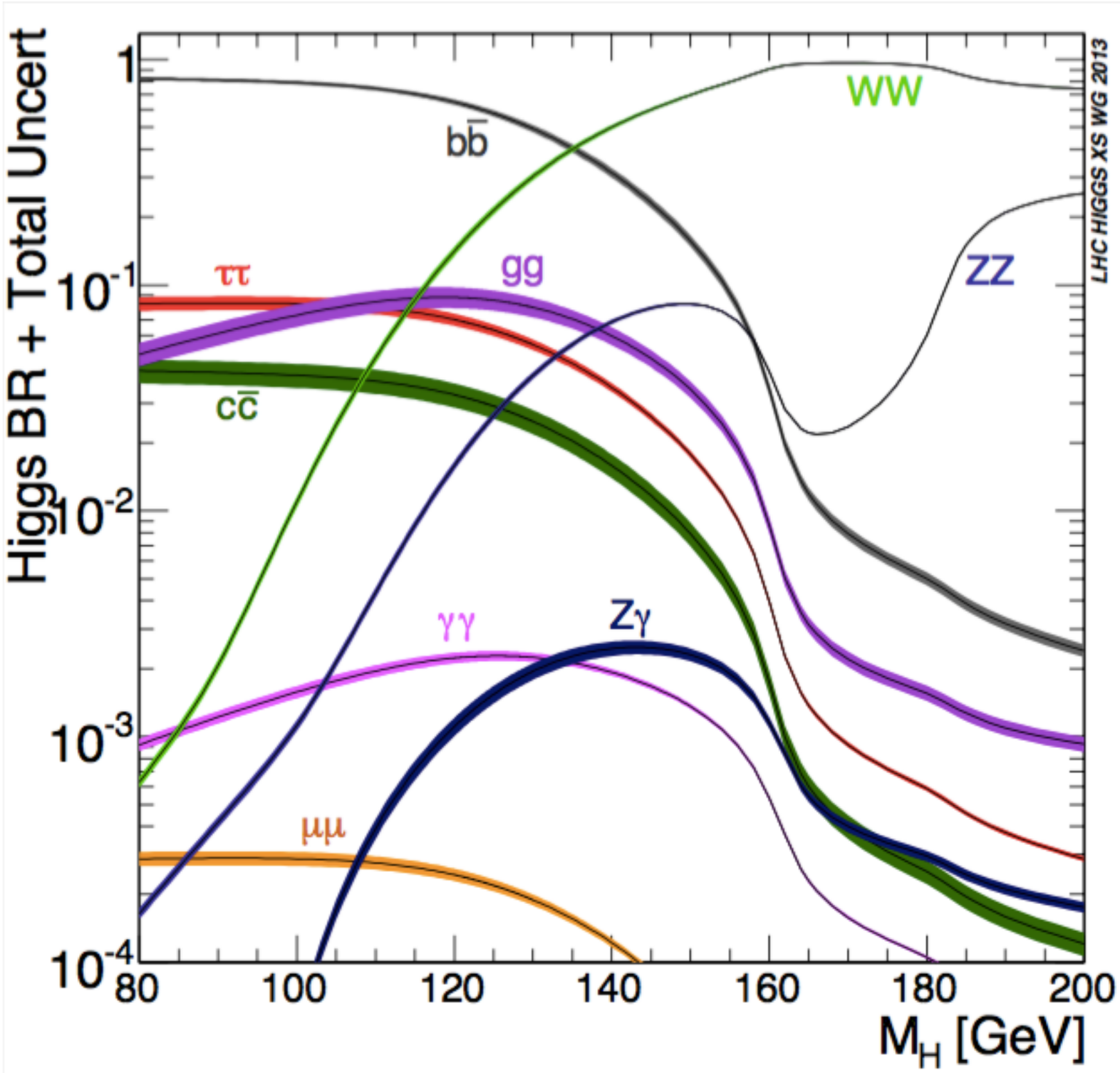
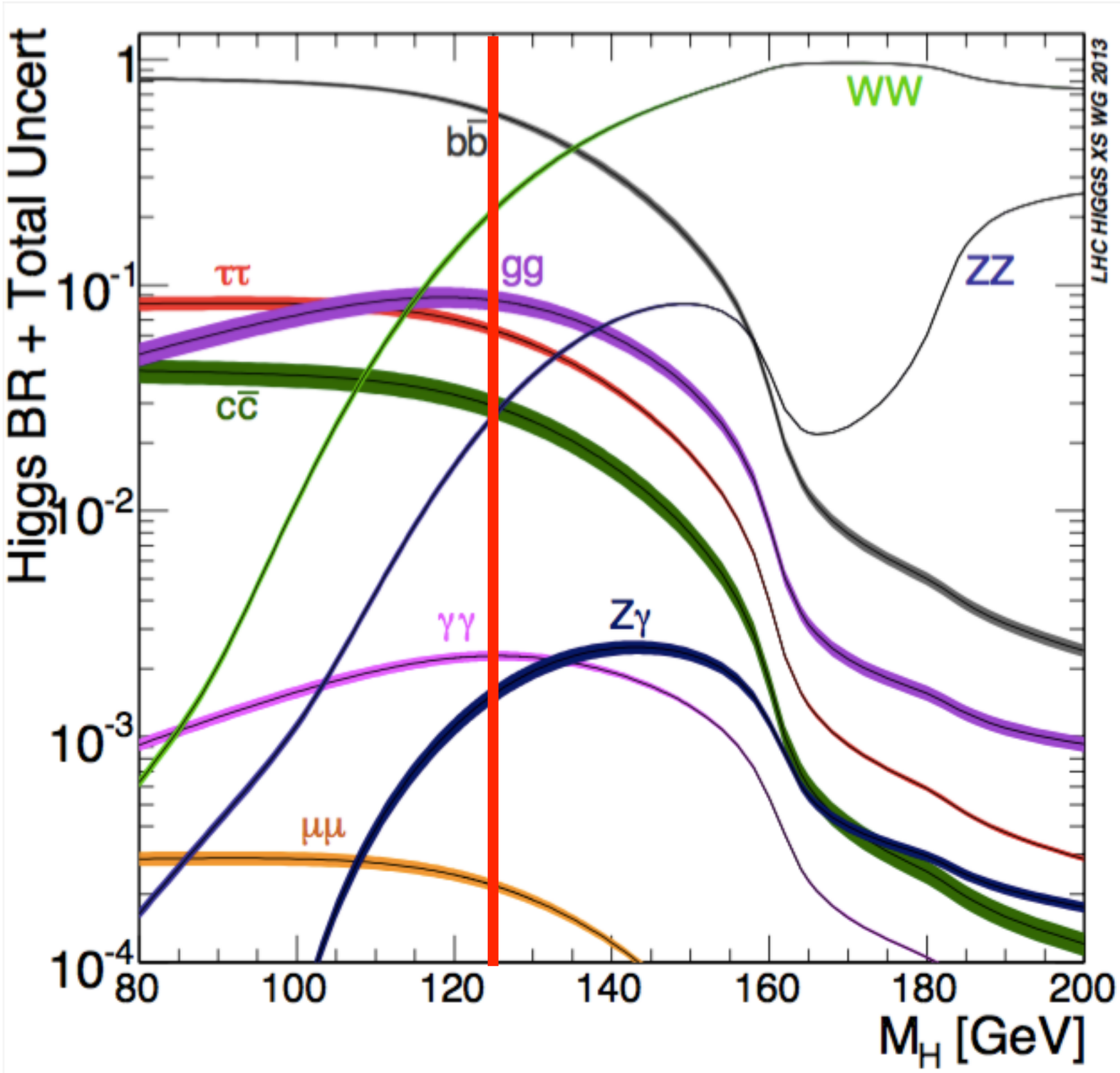

Higgs BR + Total Uncert
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
80
100
120
140
160
180
200
M_H [GeV]
bb̄
WW
ZZ
ττ
gg
cc̄
γγ
Zγ
μμ
LHC HIGGS XS WG 2013



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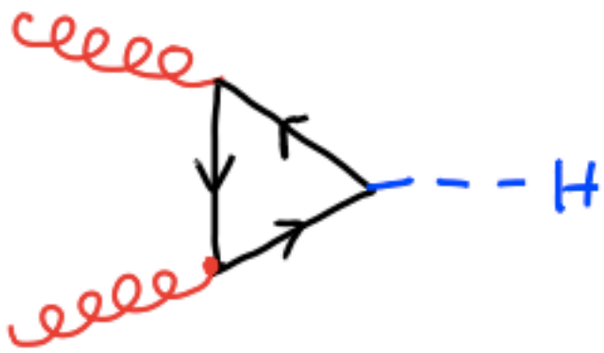
Higgs as a probe



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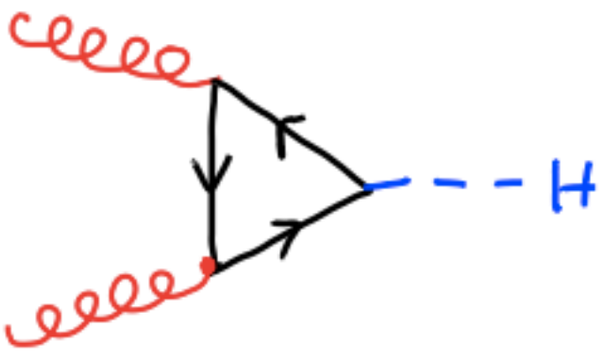

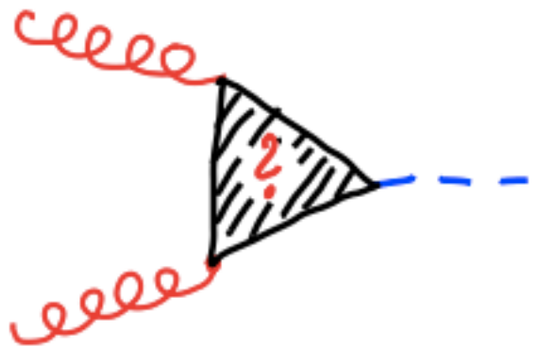

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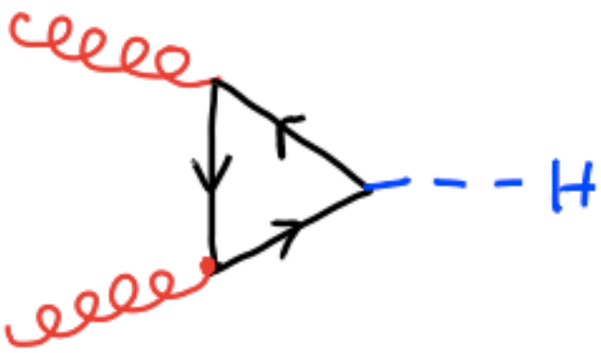

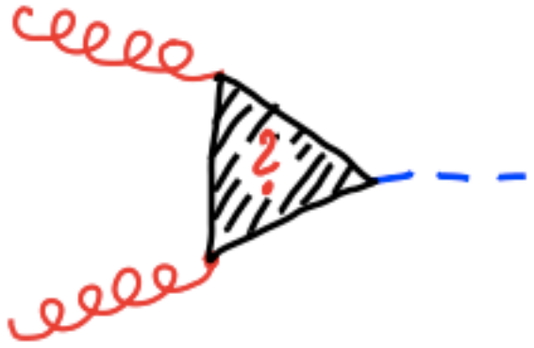

$$\sqrt{\hat{s}} = M_H$$

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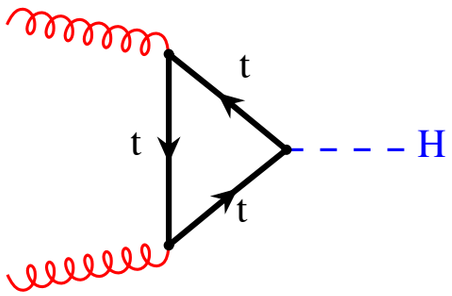
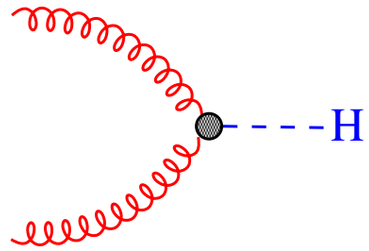
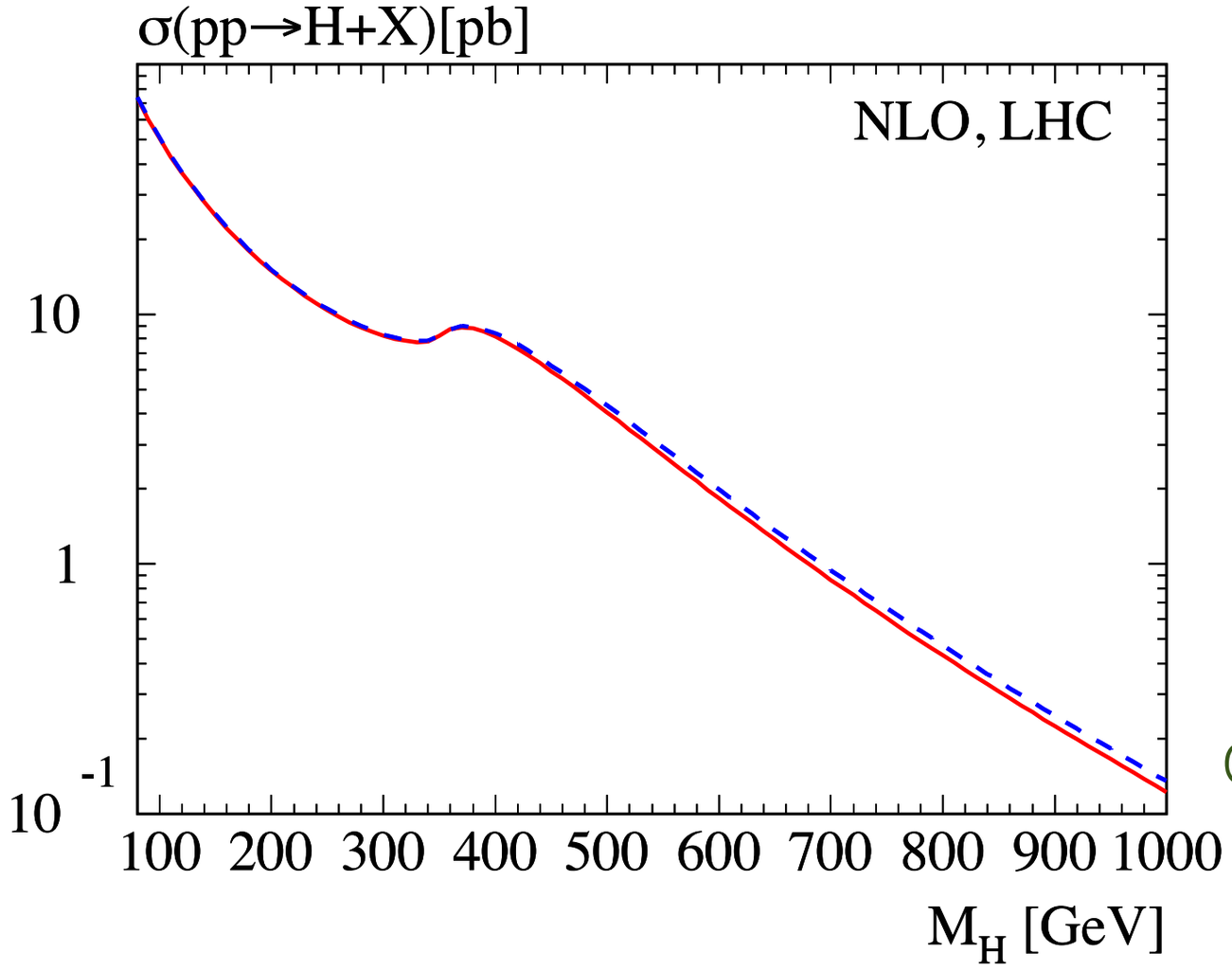
Heavy-top limit



$$m_t \gg M_H \longrightarrow C(m_t, \alpha_s) \times$$





$$\sigma_\infty^{\mathrm{HO}} \equiv \sigma^{\mathrm{LO}}(m_t) \left(\frac{\sigma^{\mathrm{HO}}}{\sigma^{\mathrm{LO}}} \right)_{m_t \to \infty}$$

Graudenz, Djouadi, Spira, Zerwas '93

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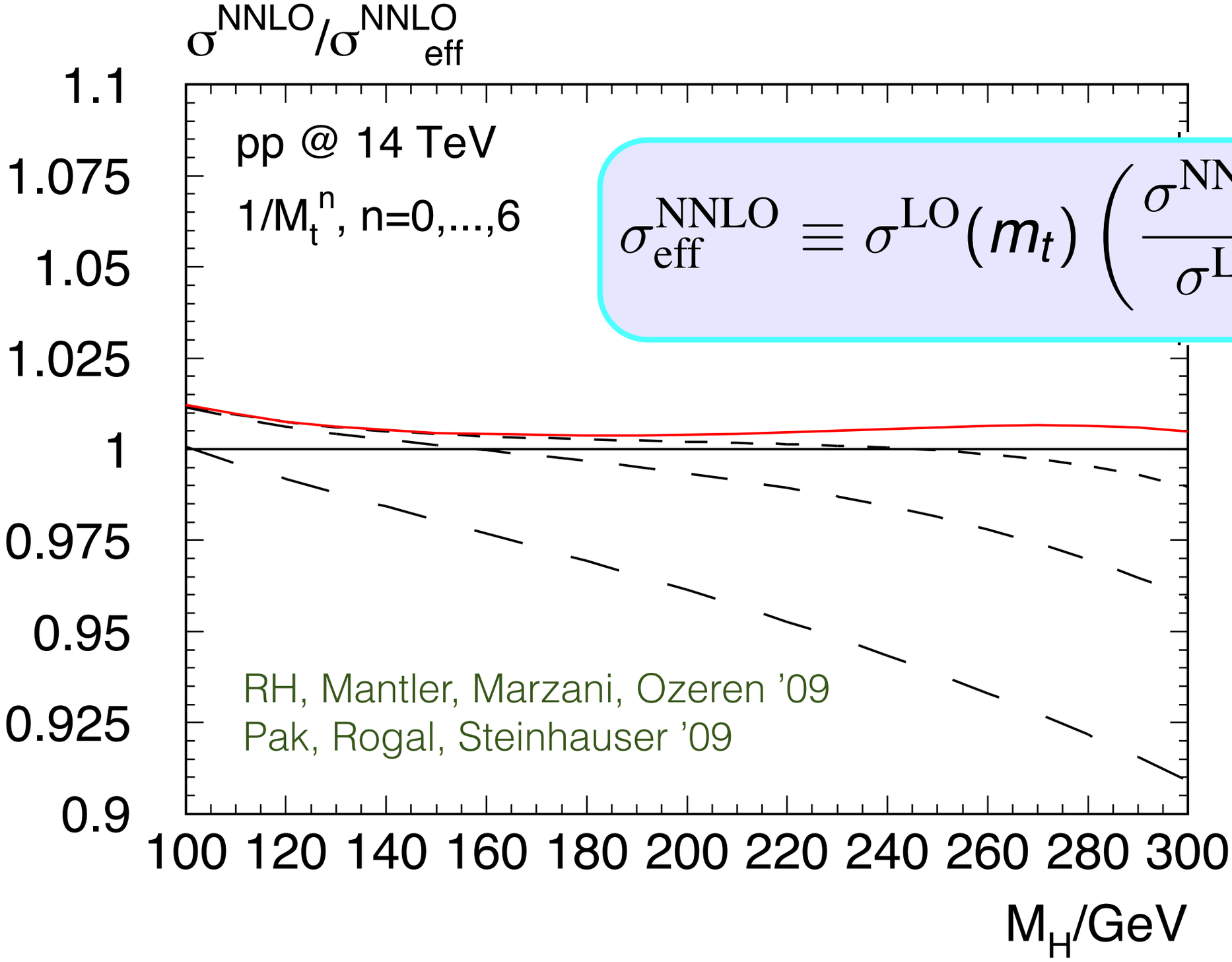

$$\sigma^{\rm NNLO}_{\rm eff} \equiv \sigma^{\rm LO}(m_t) \left(\frac{\sigma^{\rm NNLO}}{\sigma^{\rm LO}} \right)_{m_t \to \infty}$$

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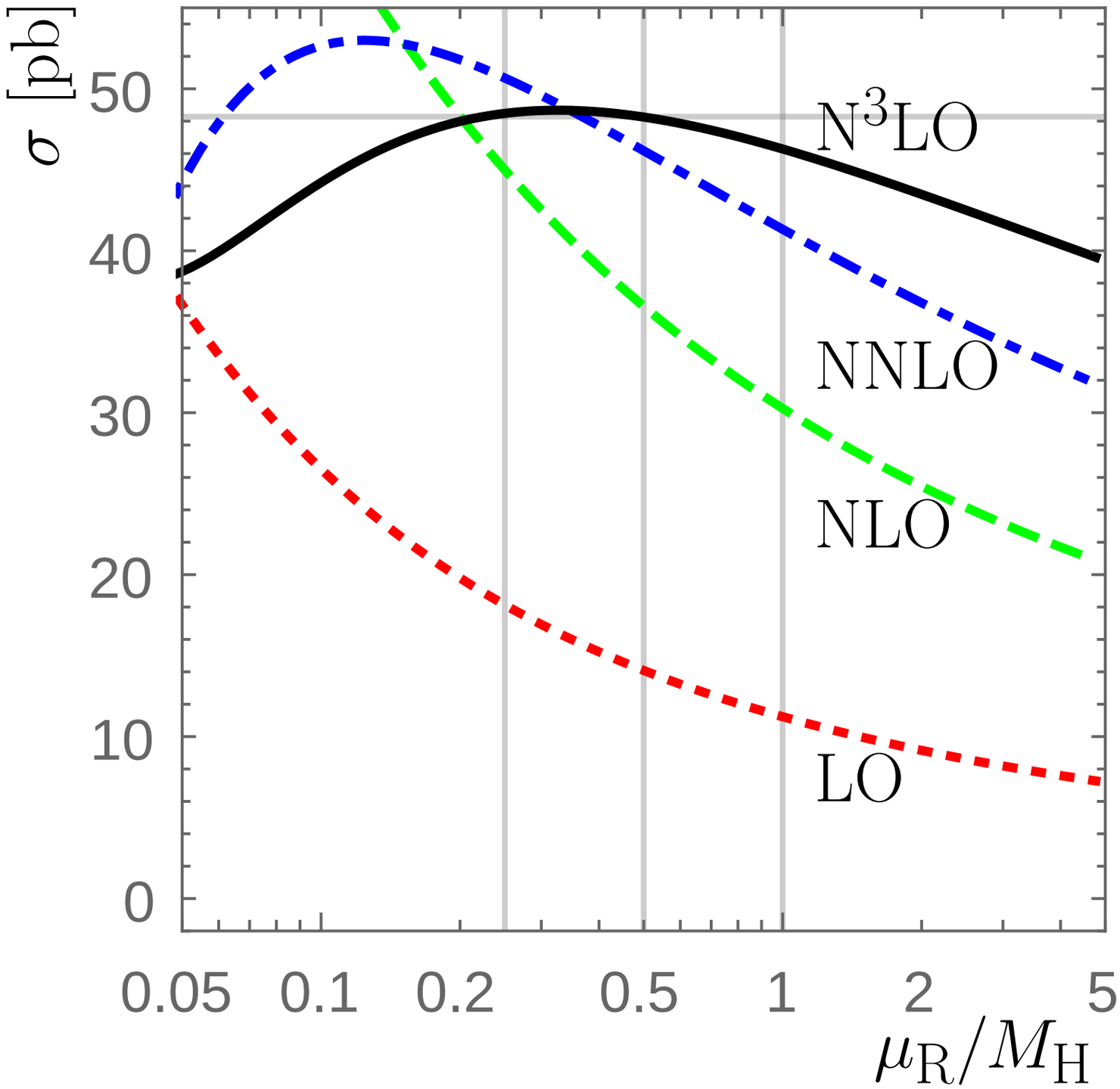
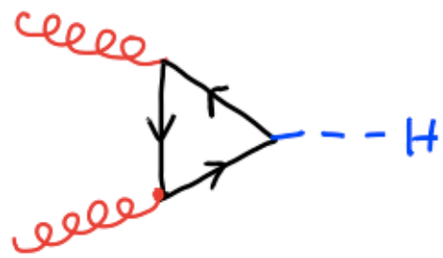
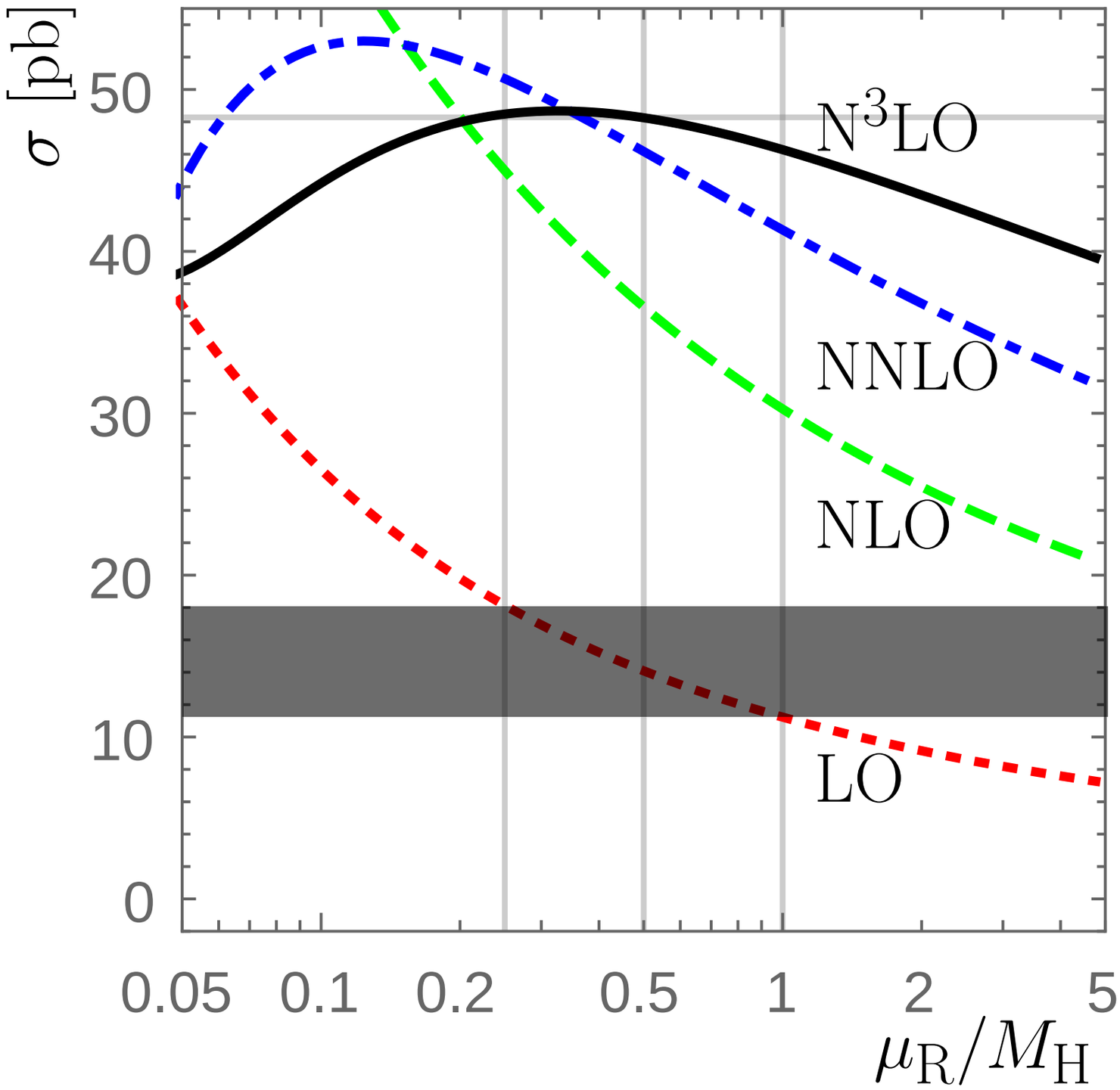
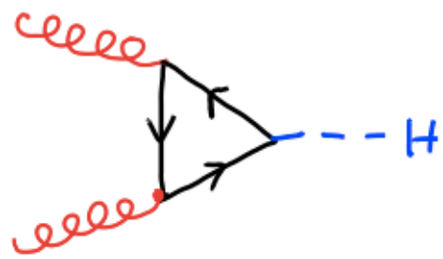
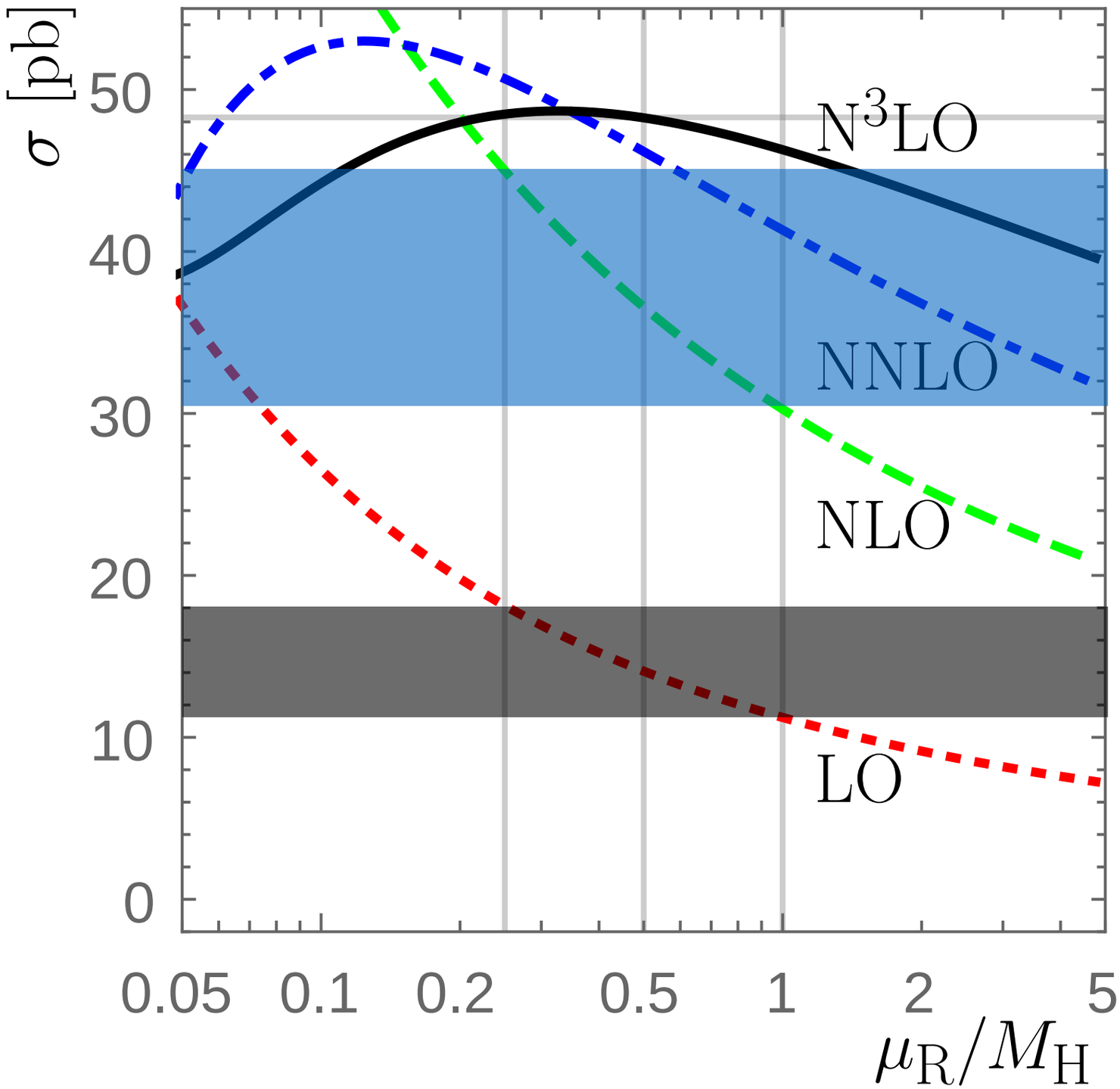

σ [pb]
50
40
30
20
10
0
0.05
0.1
0.2
0.5
1
2
5
μ_R/M_H
N³LO
NNLO
NLO
LO


H



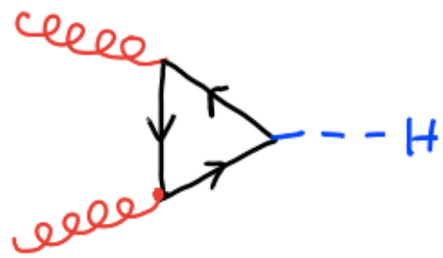
1976

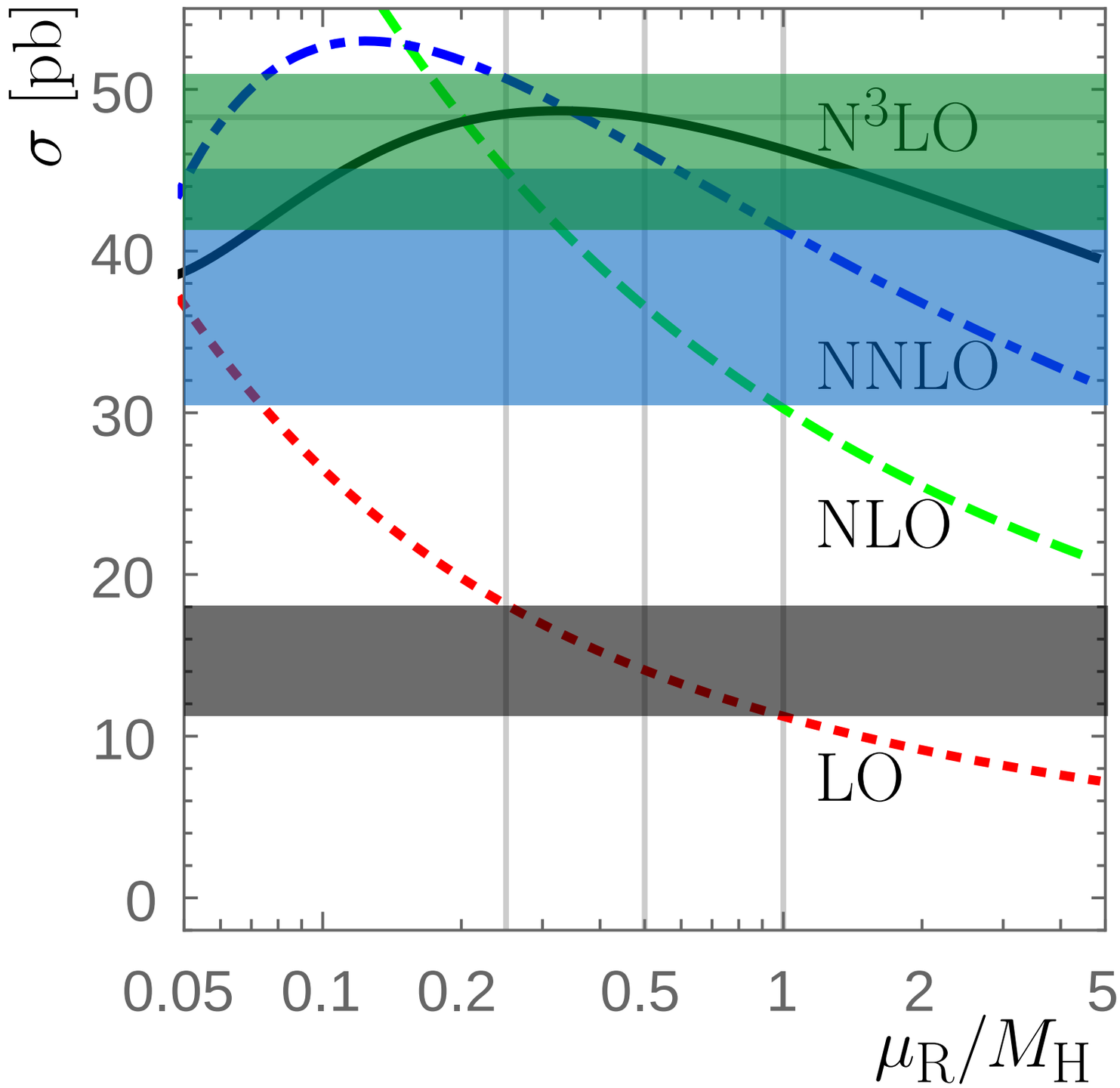




1991

1976

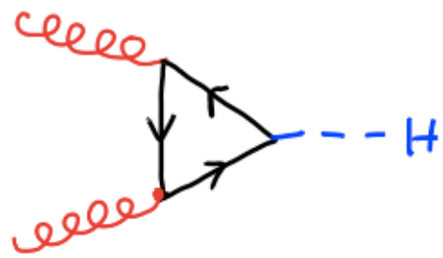


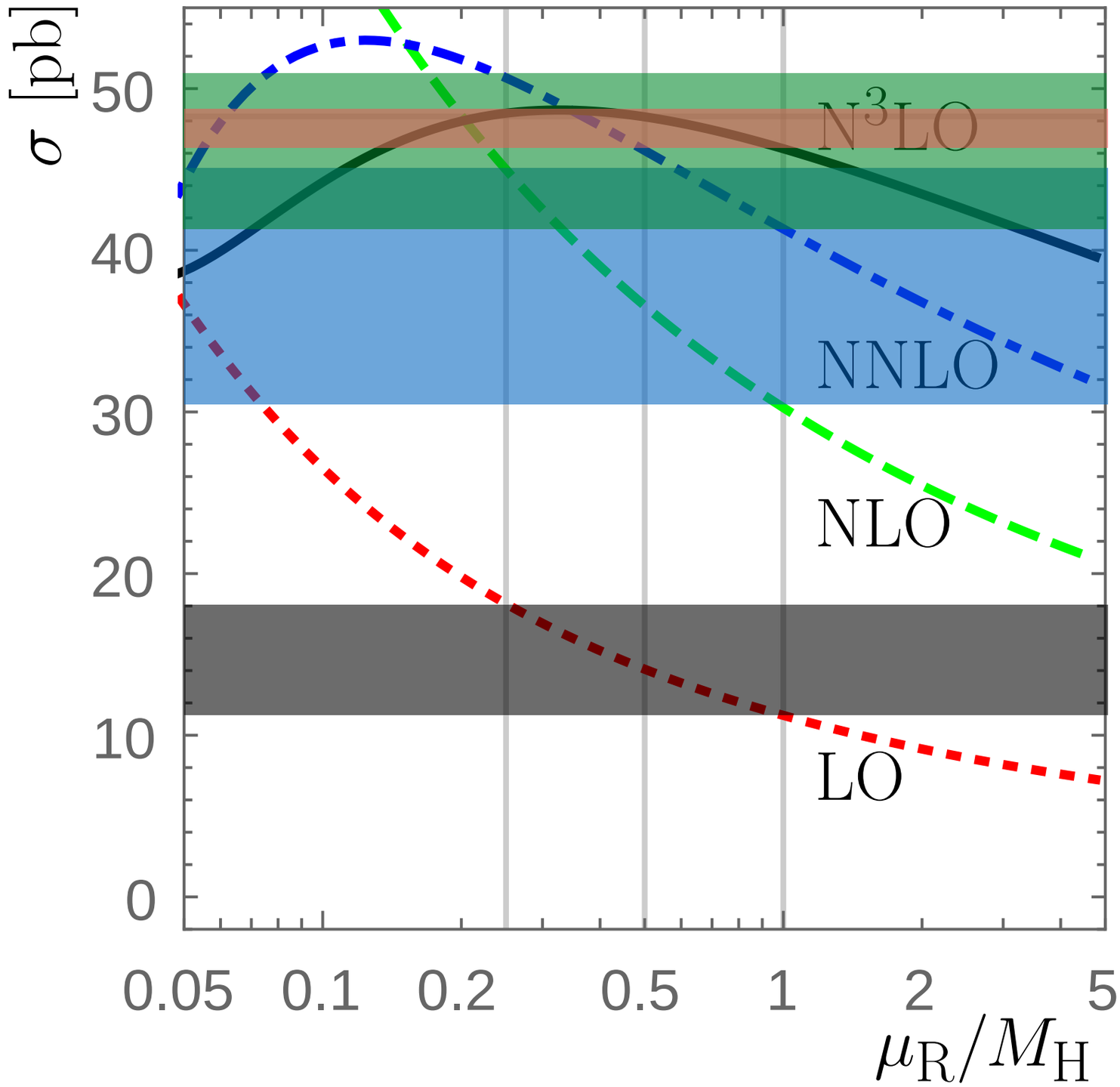


2002

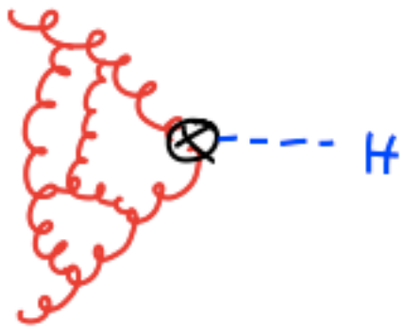
1991

1976





Anastasiou *et al.*
2015
2002



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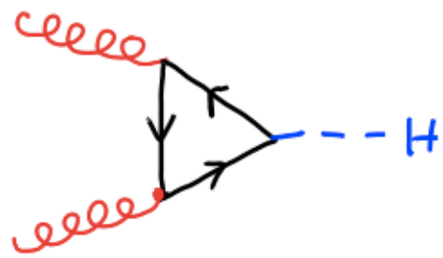


σ [pb]

50

40

30

20

10

0

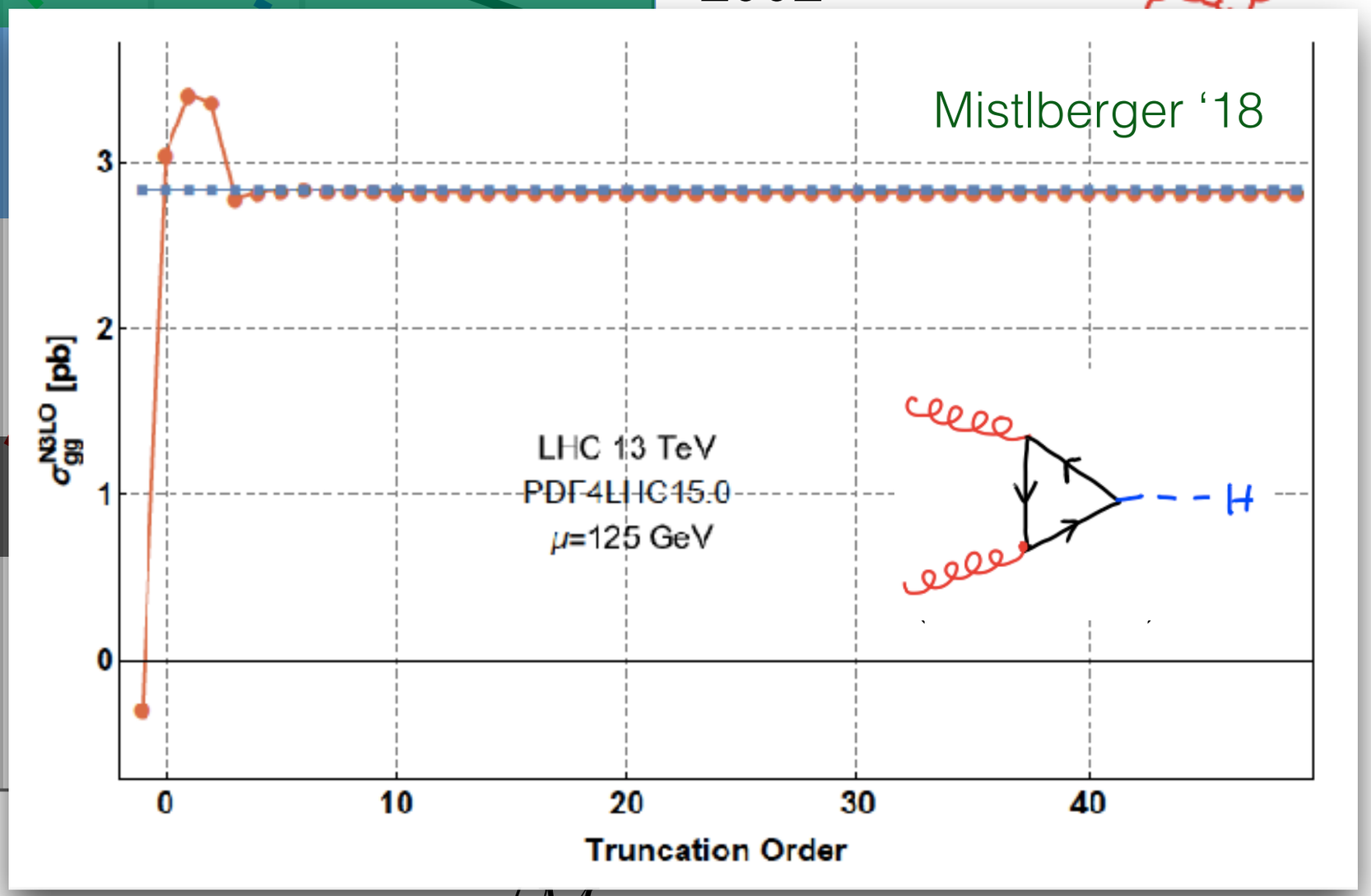
0.05 0.1 0.2

$\mu_{\rm R}/M_{\rm H}$

N^{3}LO

Anastasiou *et al.*
2015
2002

Mistlberger '18



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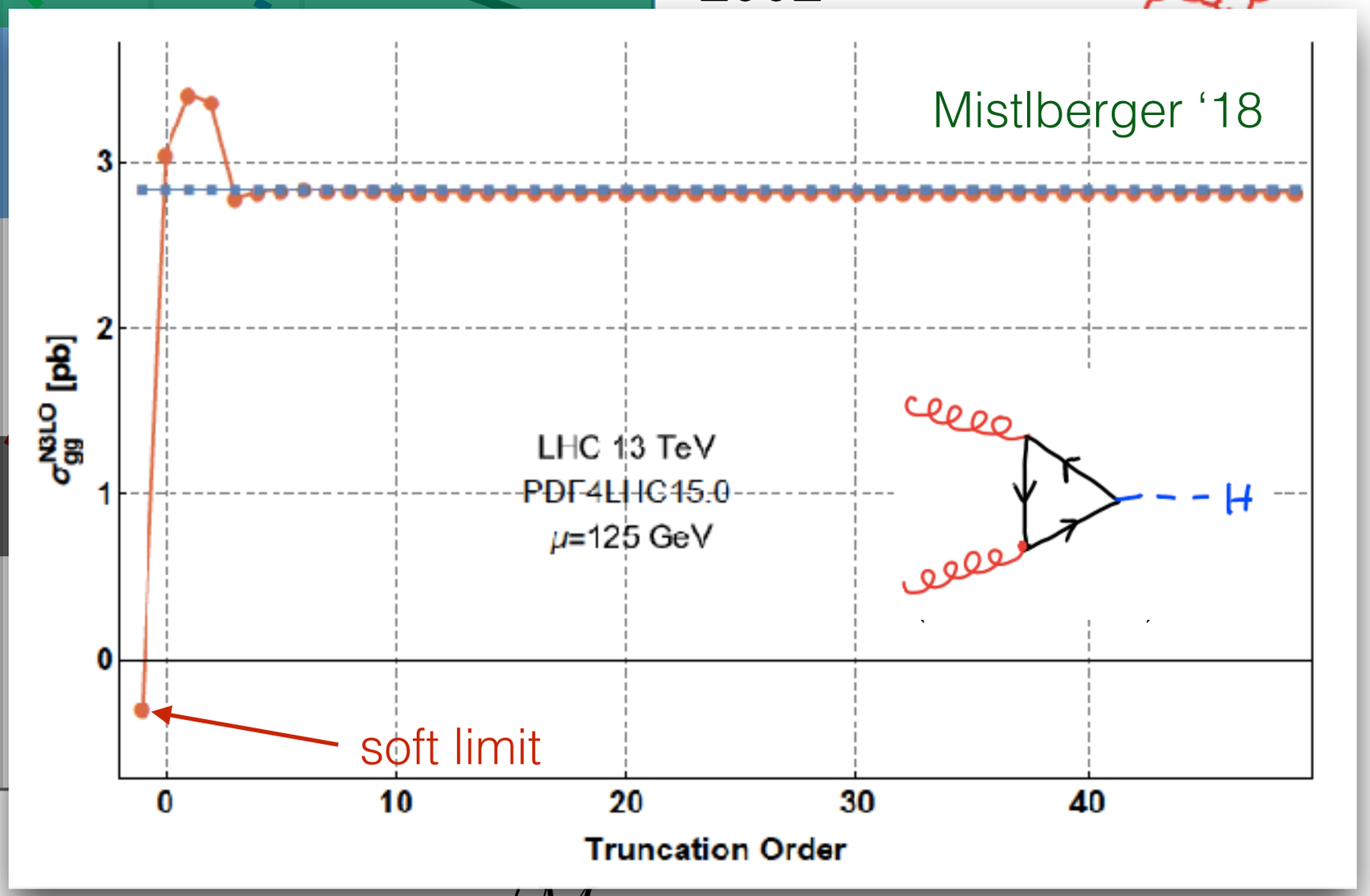
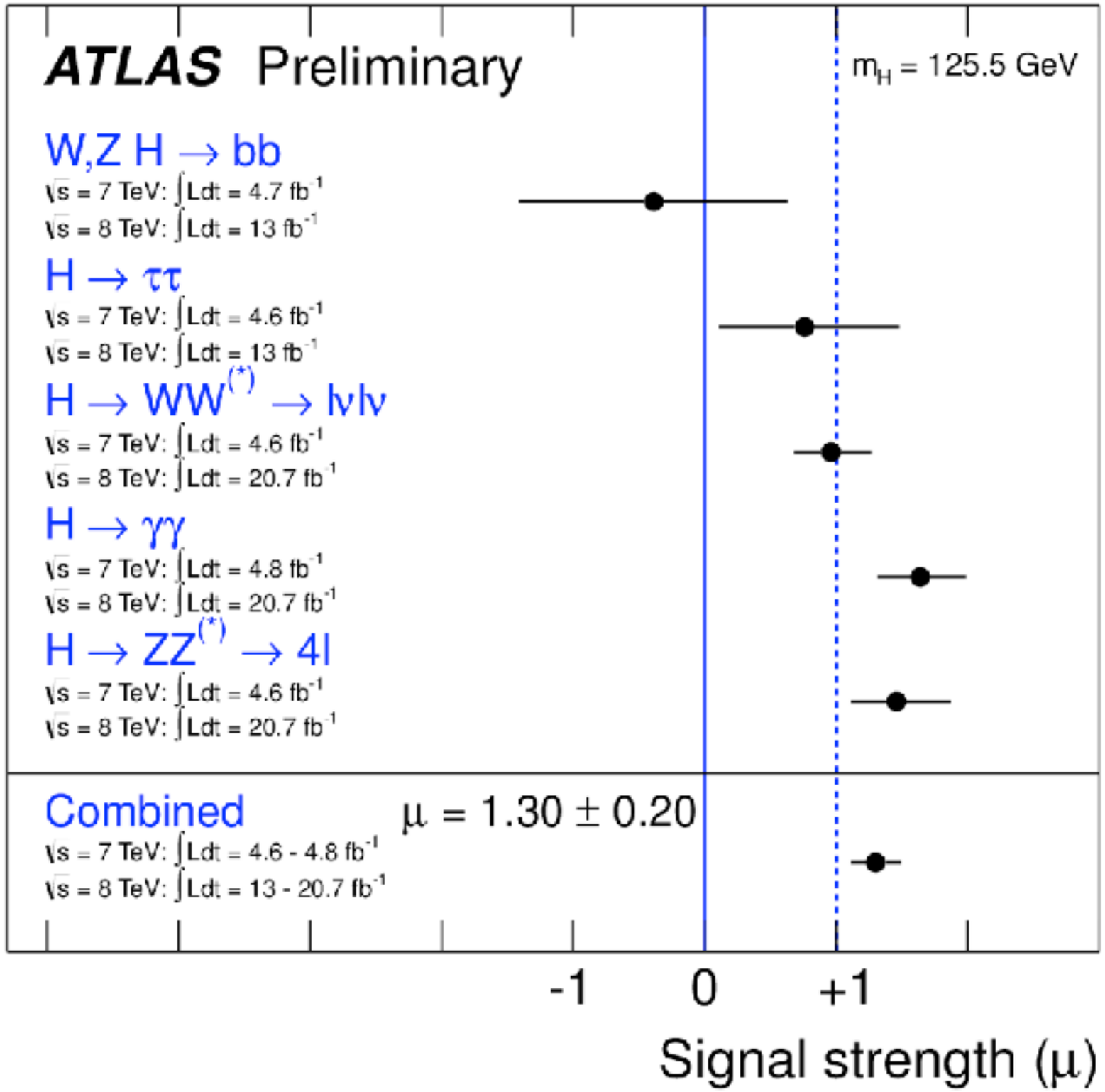
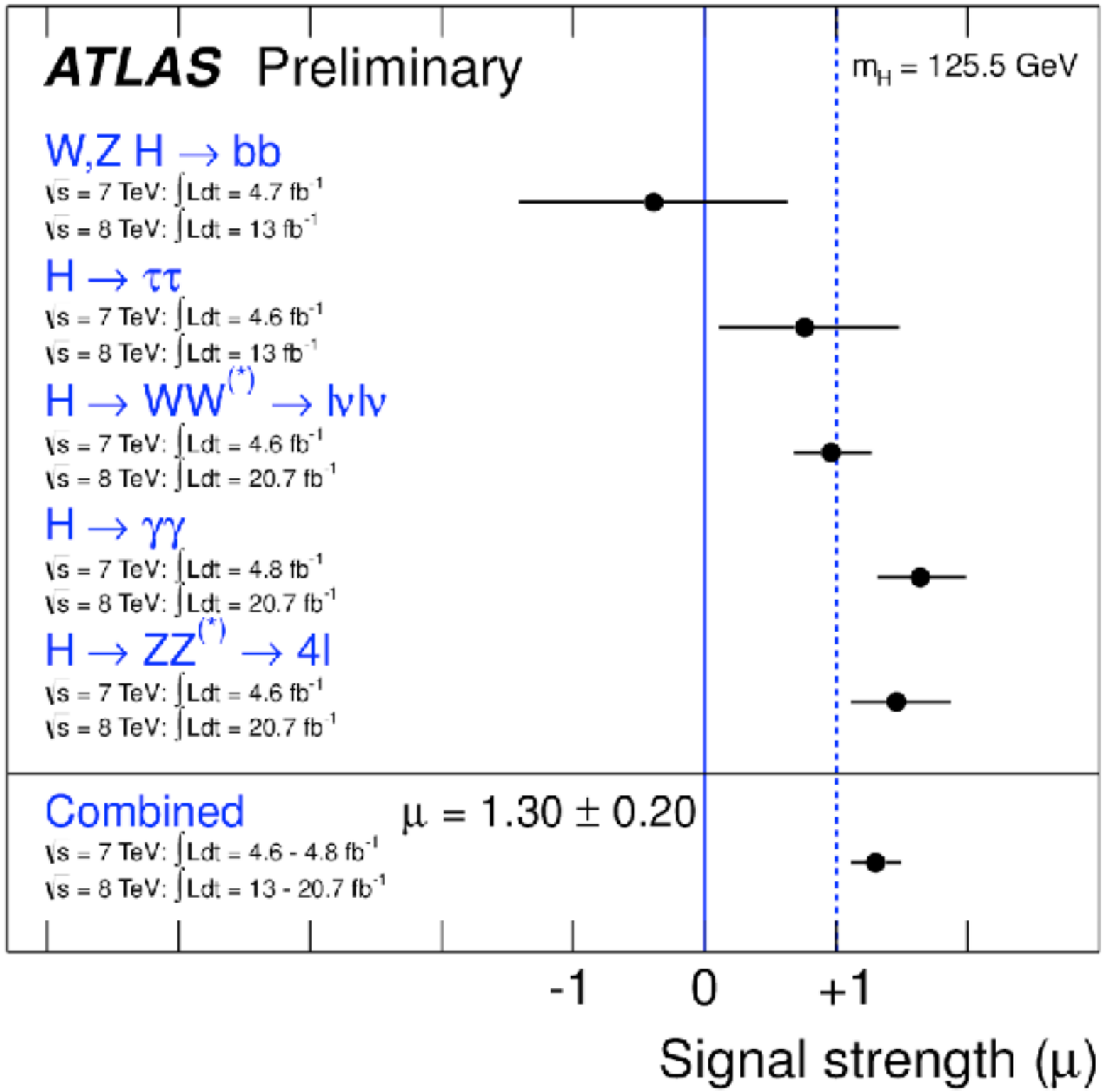



ATLAS Preliminary
m_H = 125.5 GeV
W,Z H → bb
√s = 7 TeV: ∫Ldt = 4.7 fb⁻¹
√s = 8 TeV: ∫Ldt = 13 fb⁻¹
H → ττ
√s = 7 TeV: ∫Ldt = 4.6 fb⁻¹
√s = 8 TeV: ∫Ldt = 13 fb⁻¹
H → WW(*) → lνlν
√s = 7 TeV: ∫Ldt = 4.6 fb⁻¹
√s = 8 TeV: ∫Ldt = 20.7 fb⁻¹
H → γγ
√s = 7 TeV: ∫Ldt = 4.8 fb⁻¹
√s = 8 TeV: ∫Ldt = 20.7 fb⁻¹
H → ZZ(*) → 4l
√s = 7 TeV: ∫Ldt = 4.6 fb⁻¹
√s = 8 TeV: ∫Ldt = 20.7 fb⁻¹
Combined
μ = 1.30 ± 0.20
√s = 7 TeV: ∫Ldt = 4.6 - 4.8 fb⁻¹
√s = 8 TeV: ∫Ldt = 13 - 20.7 fb⁻¹
-1
0
+1
Signal strength (μ)

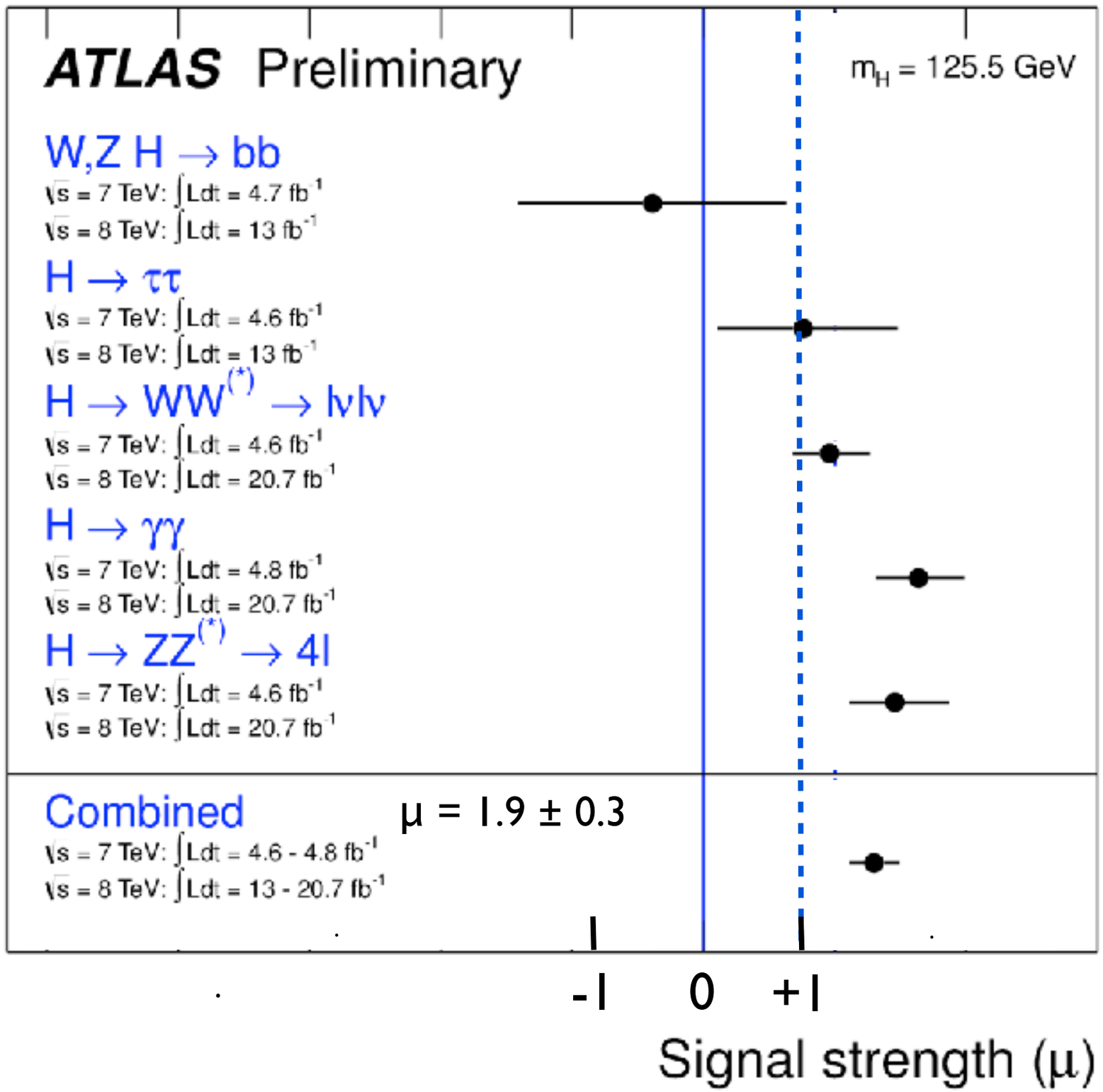
March 2013

NNLO



March 2013

NLO



highly unofficial and scetchy!

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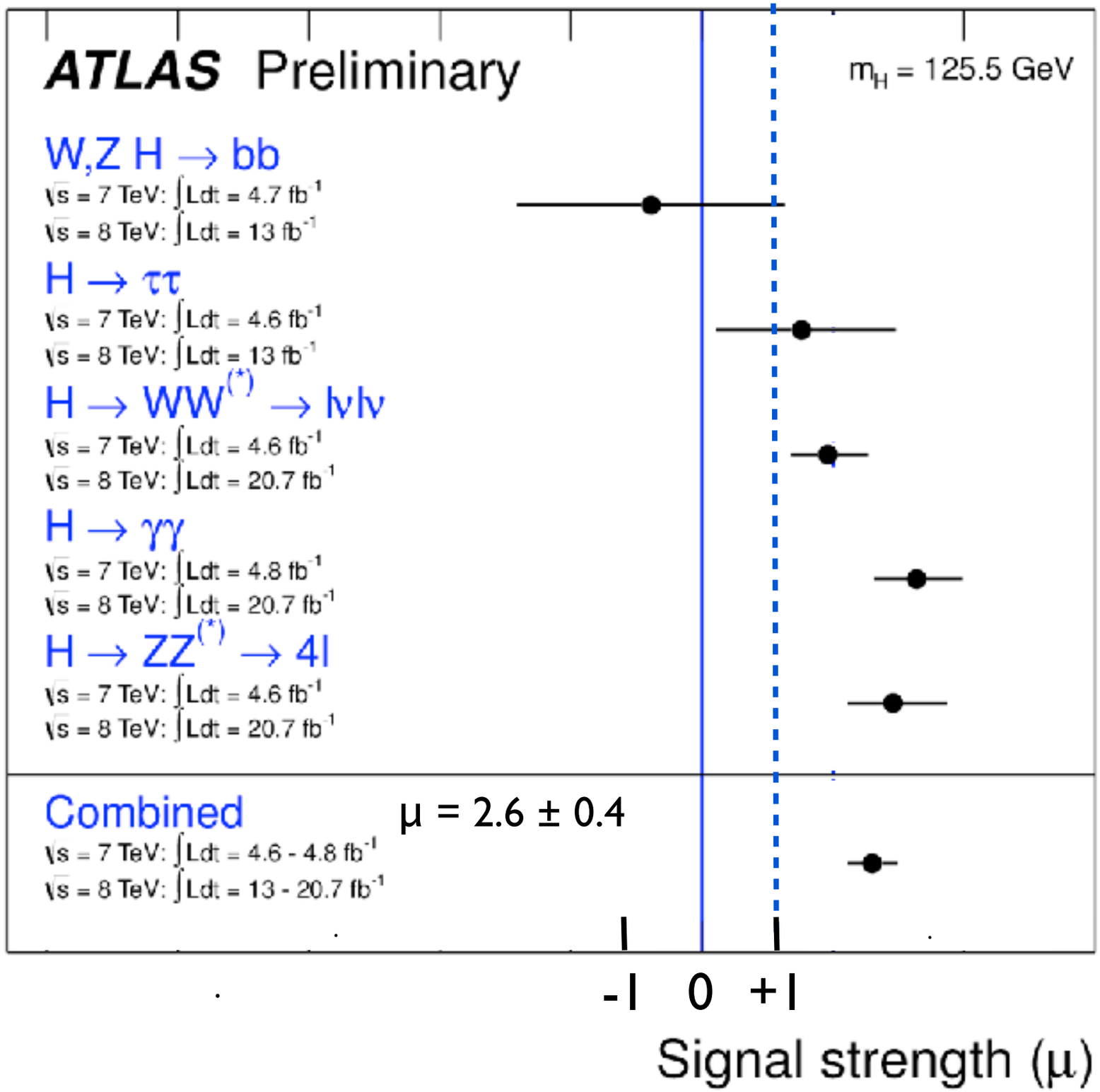
LO



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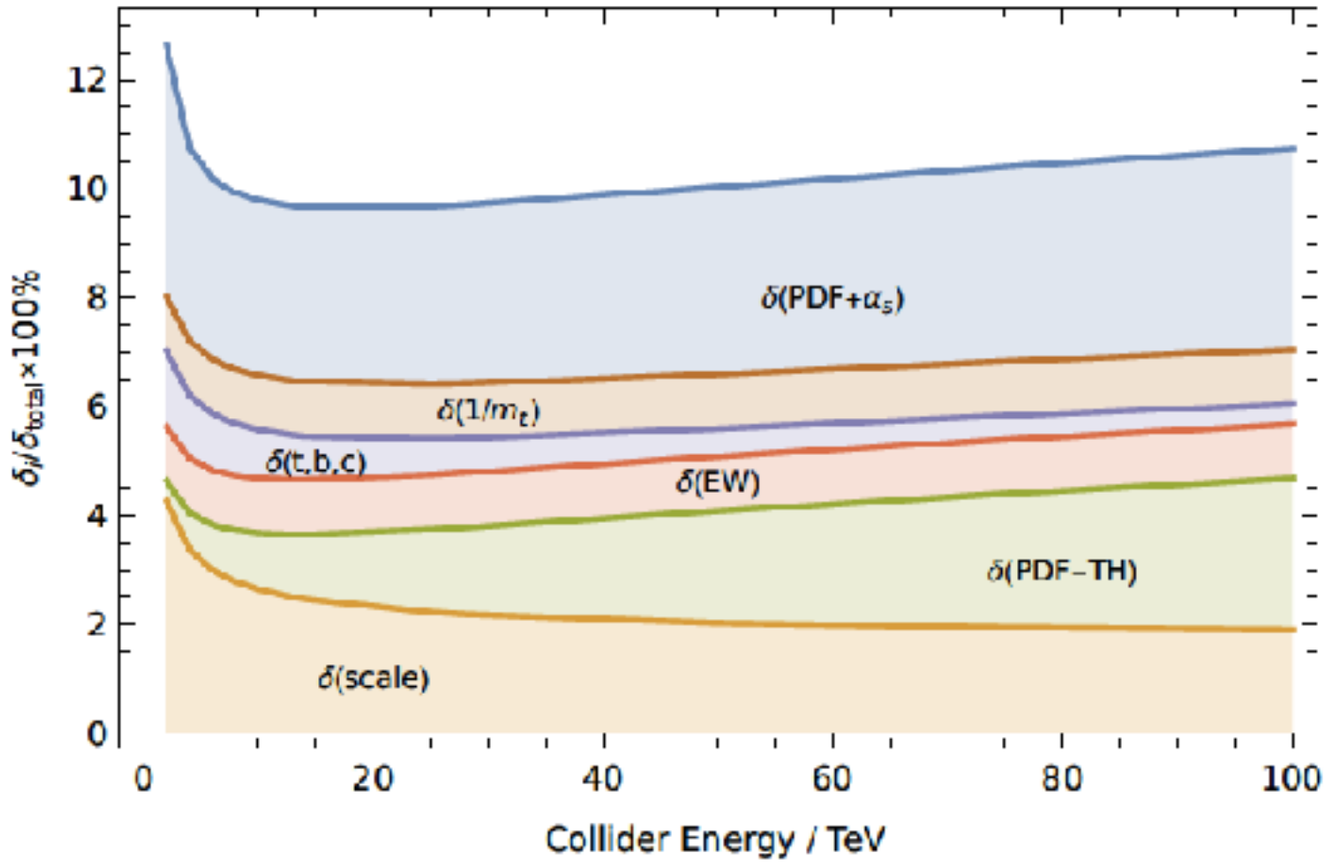
Total cross section

$\sqrt{s}$	σ	δ(theory)	δ(PDF)	$\delta(\alpha_s)$
13 TeV	48.61 pb	$^{+2.08\text{pb}}_{-3.15\text{pb}}$ $\left(^{+4.27\%}_{-6.49\%}\right)$	± 0.89 pb ($\pm 1.85\%$)	$^{+1.24\text{pb}}_{-1.26\text{pb}}$ $\left(^{+2.59\%}_{-2.62\%}\right)$
14 TeV	54.72 pb	$^{+2.35\text{pb}}_{-3.54\text{pb}}$ $\left(^{+4.28\%}_{-6.46\%}\right)$	± 1.00 pb ($\pm 1.85\%$)	$^{+1.40\text{pb}}_{-1.41\text{pb}}$ $\left(^{+2.60\%}_{-2.62\%}\right)$
27 TeV	146.65 pb	$^{+6.65\text{pb}}_{-9.44\text{pb}}$ $\left(^{+4.53\%}_{-6.43\%}\right)$	± 2.81 pb ($\pm 1.95\%$)	$^{+3.88\text{pb}}_{-3.82\text{pb}}$ $\left(^{+2.69\%}_{-2.64\%}\right)$



QCD/EW:
complete factorization
Anastasiou, Boughezal, Petriello '09

Checked by
explicit calculations:
Bonetti, Melnikov, Tancredi '17
Anastasiou *et al.* '18

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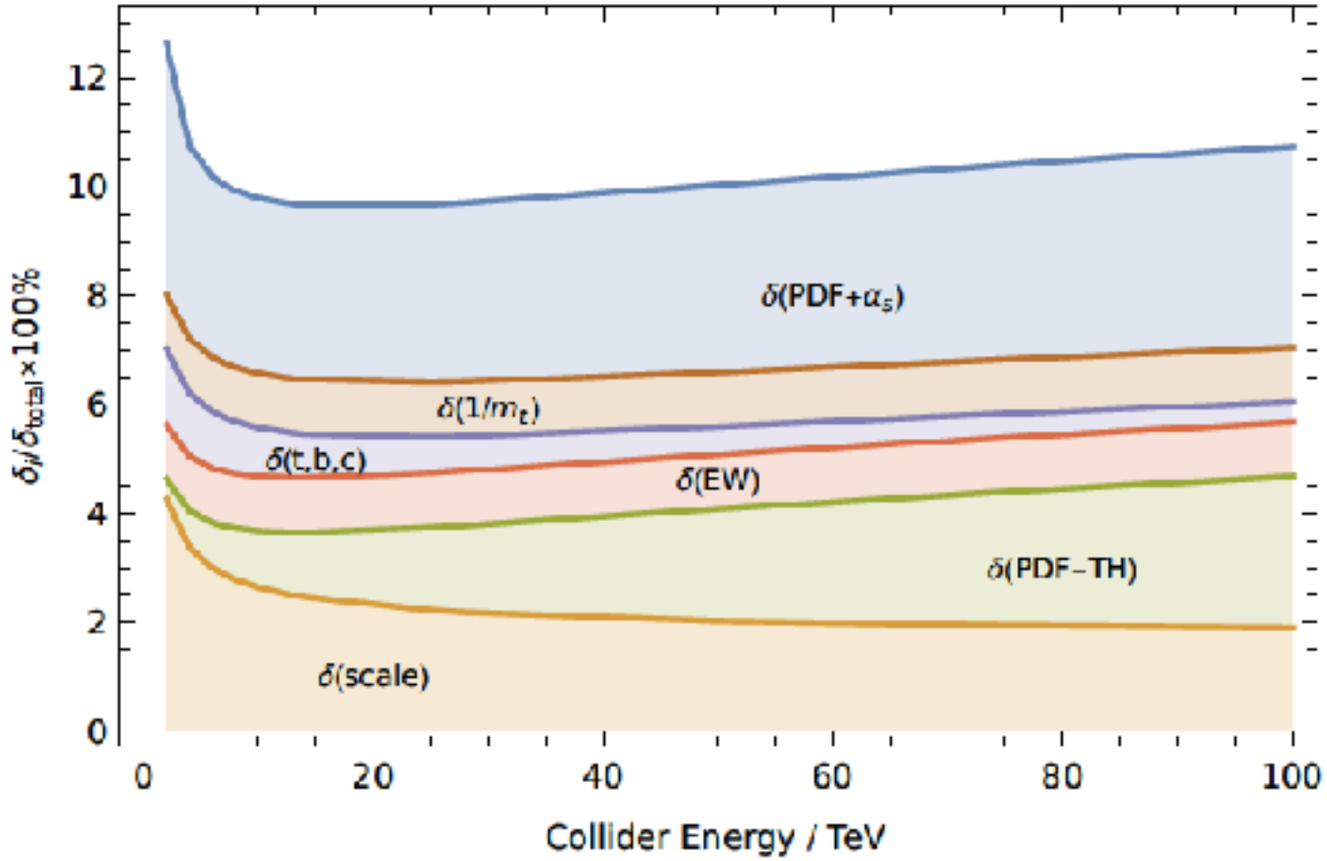

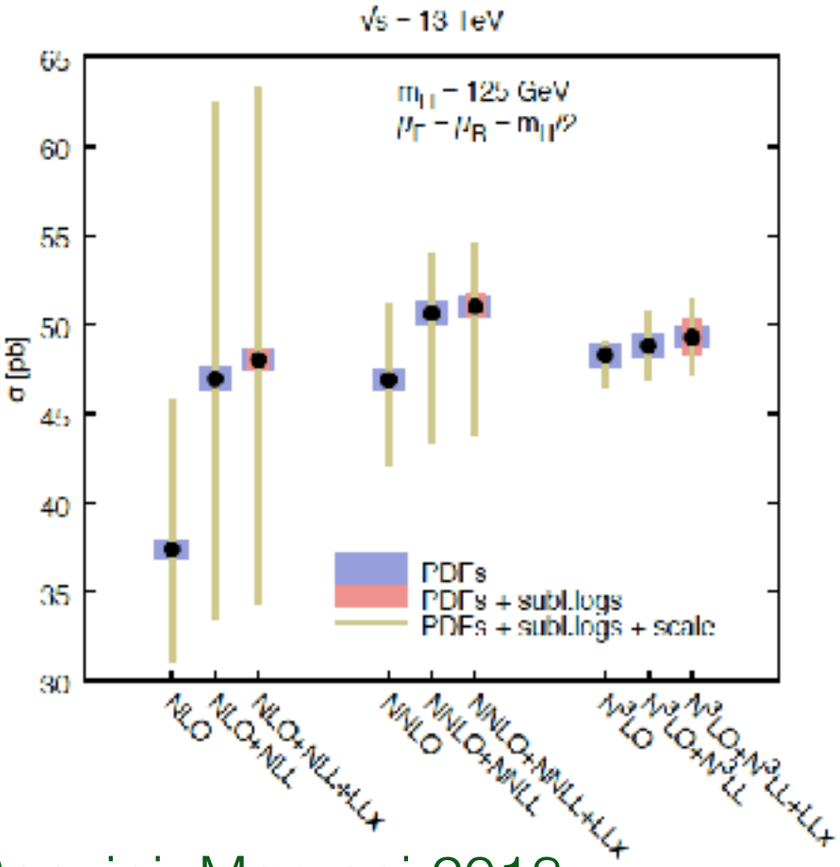

Bonvini, Marzani 2018

R. Harlander, *SM Higgs precision calculations*, June 2019

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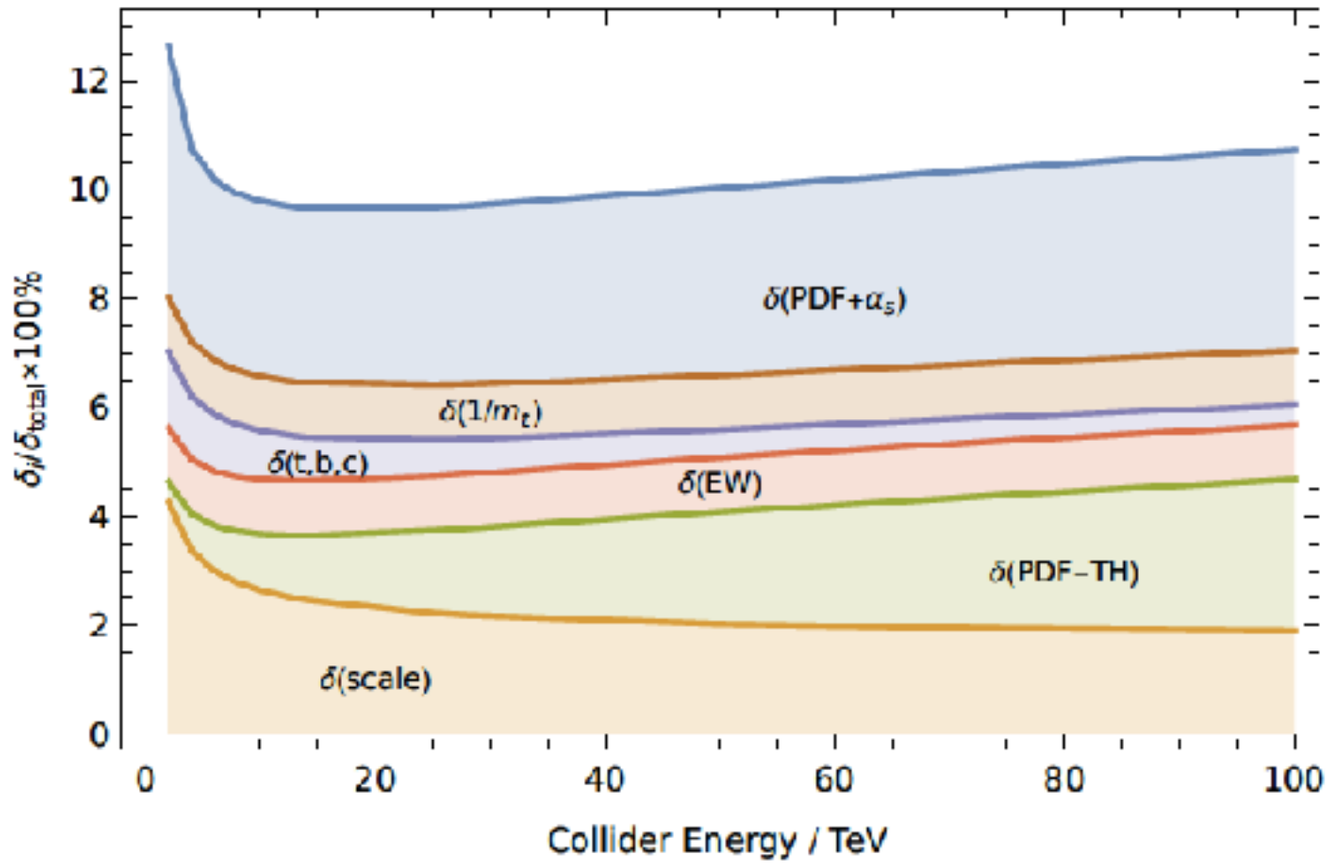

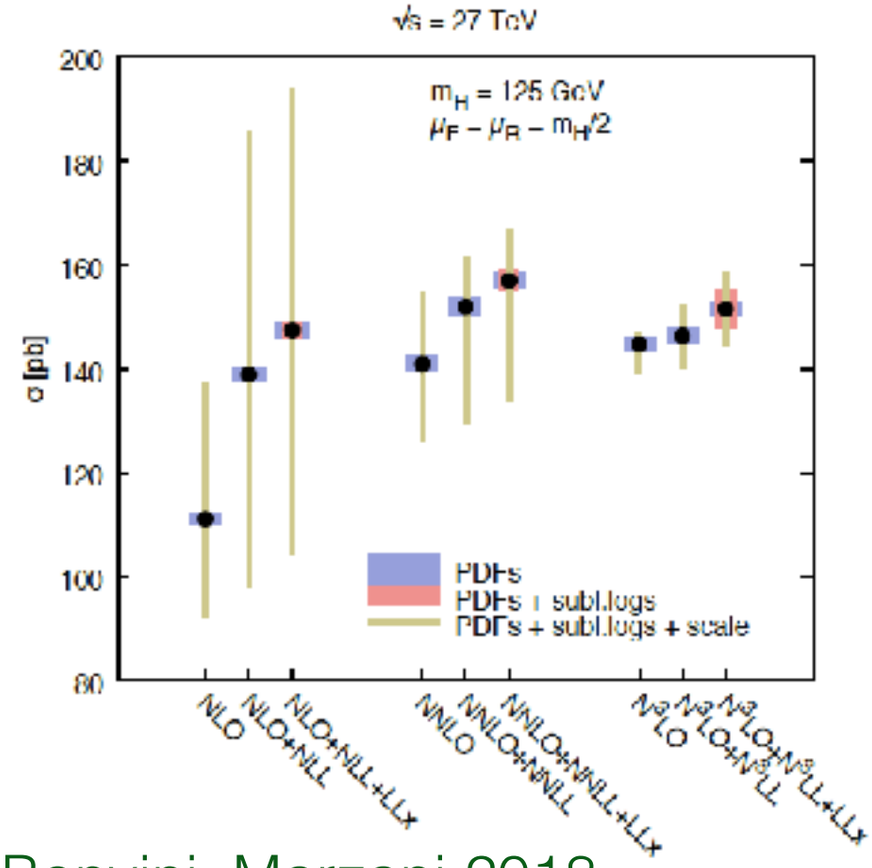

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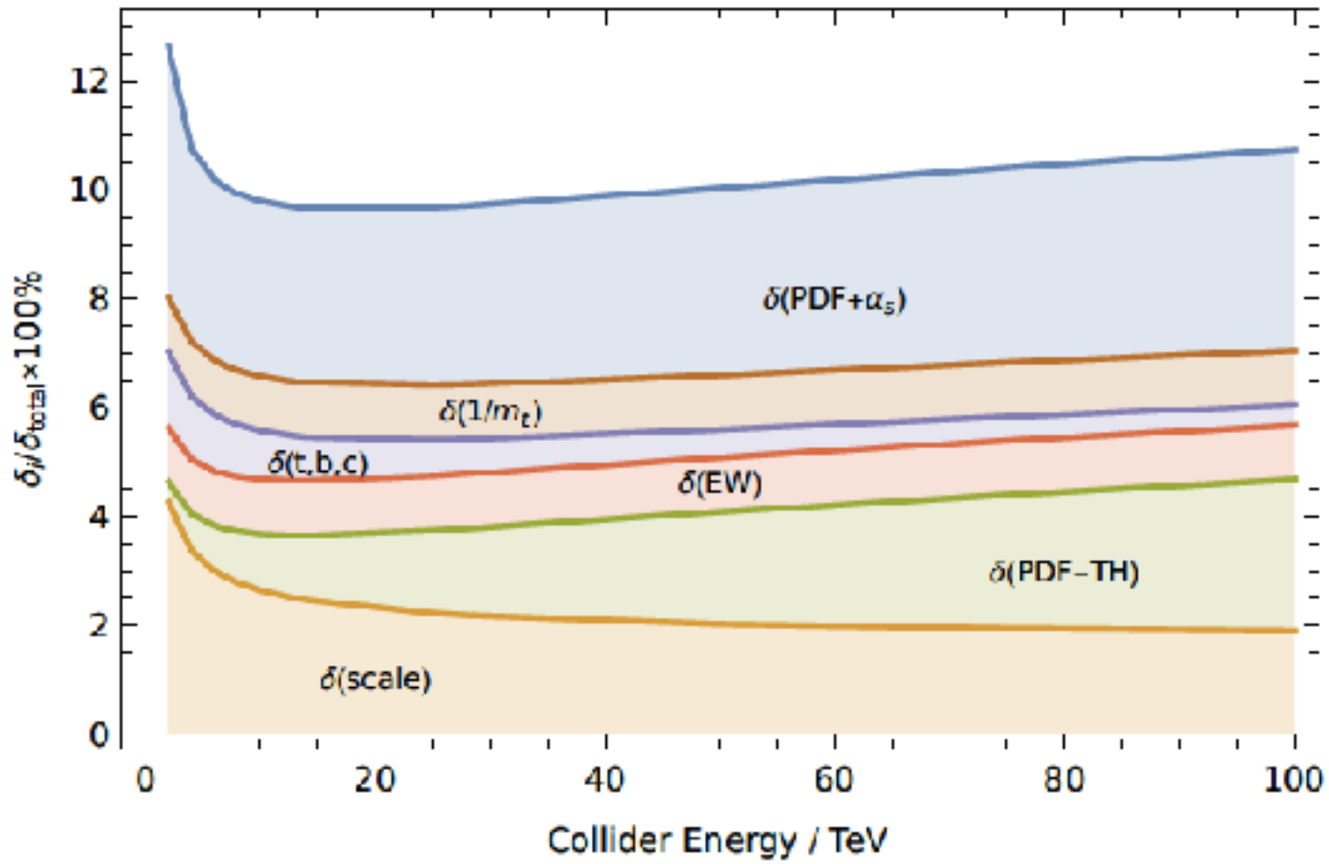

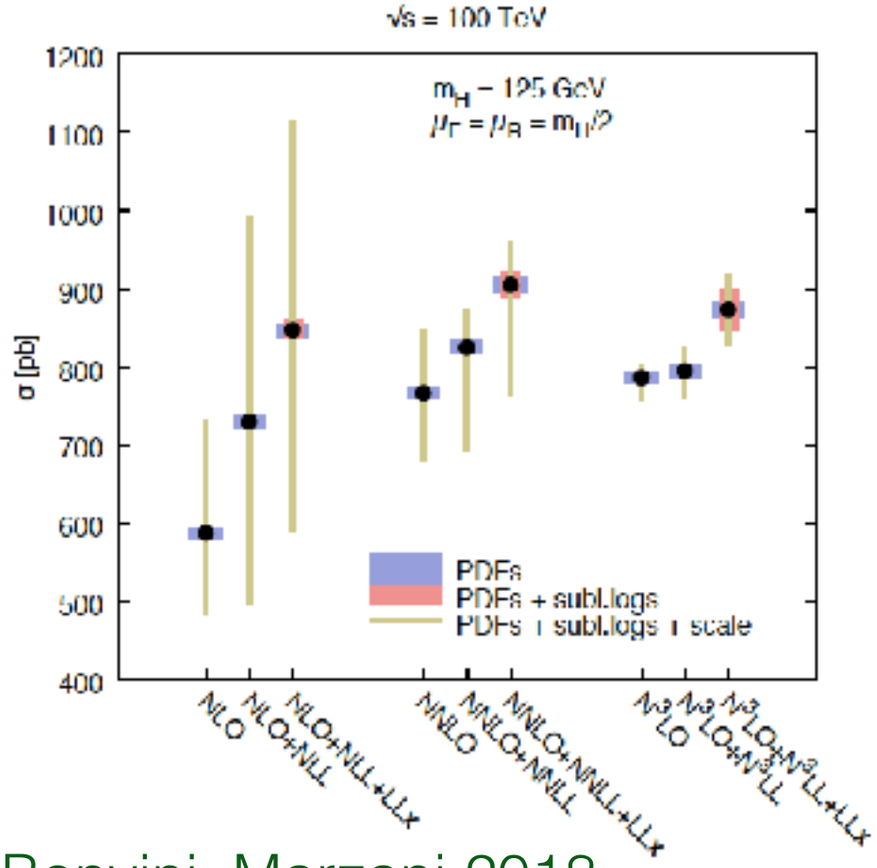

Bonvini, Marzani 2018

R. Harlander, *SM Higgs precision calculations*, June 2019

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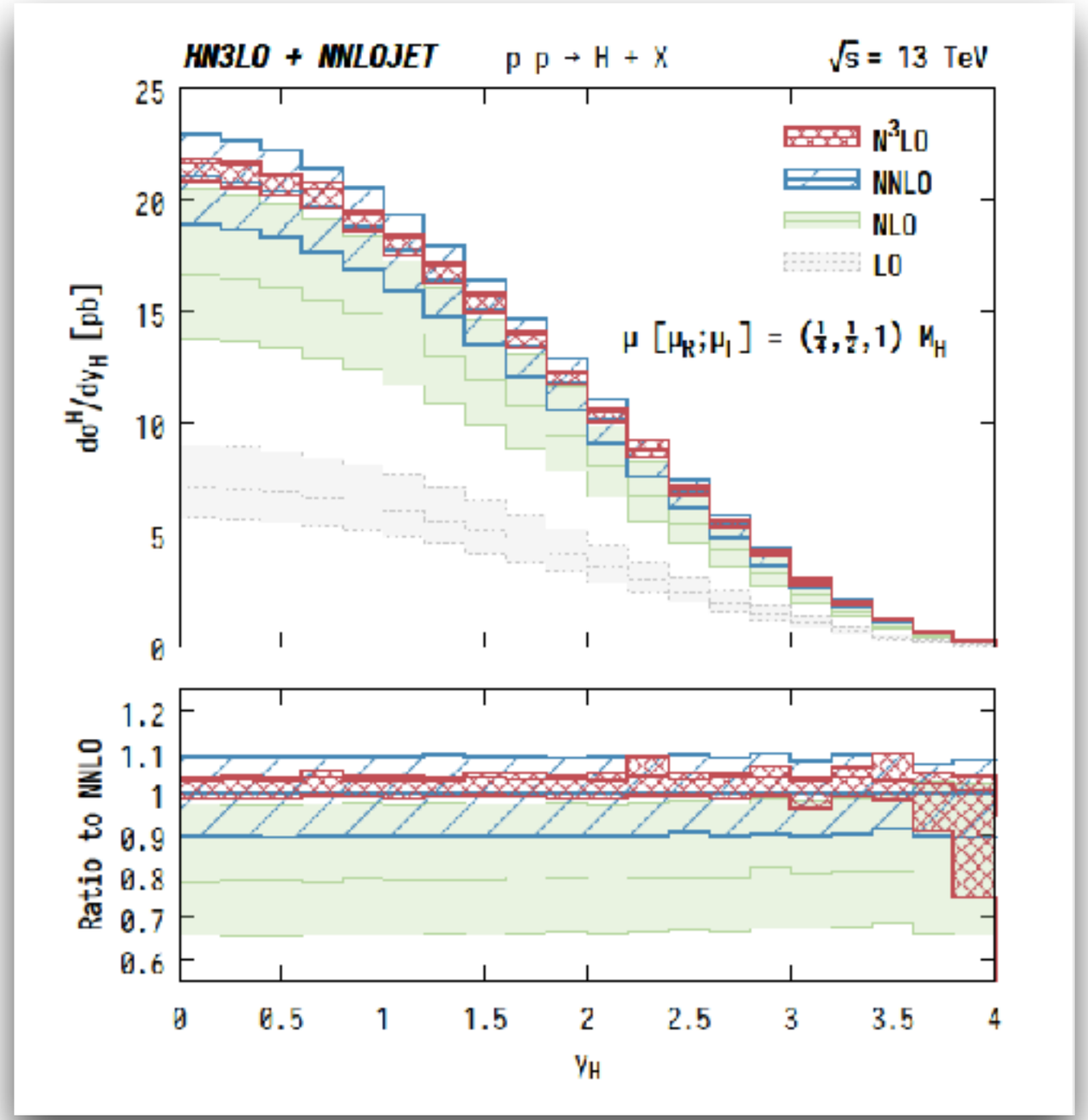
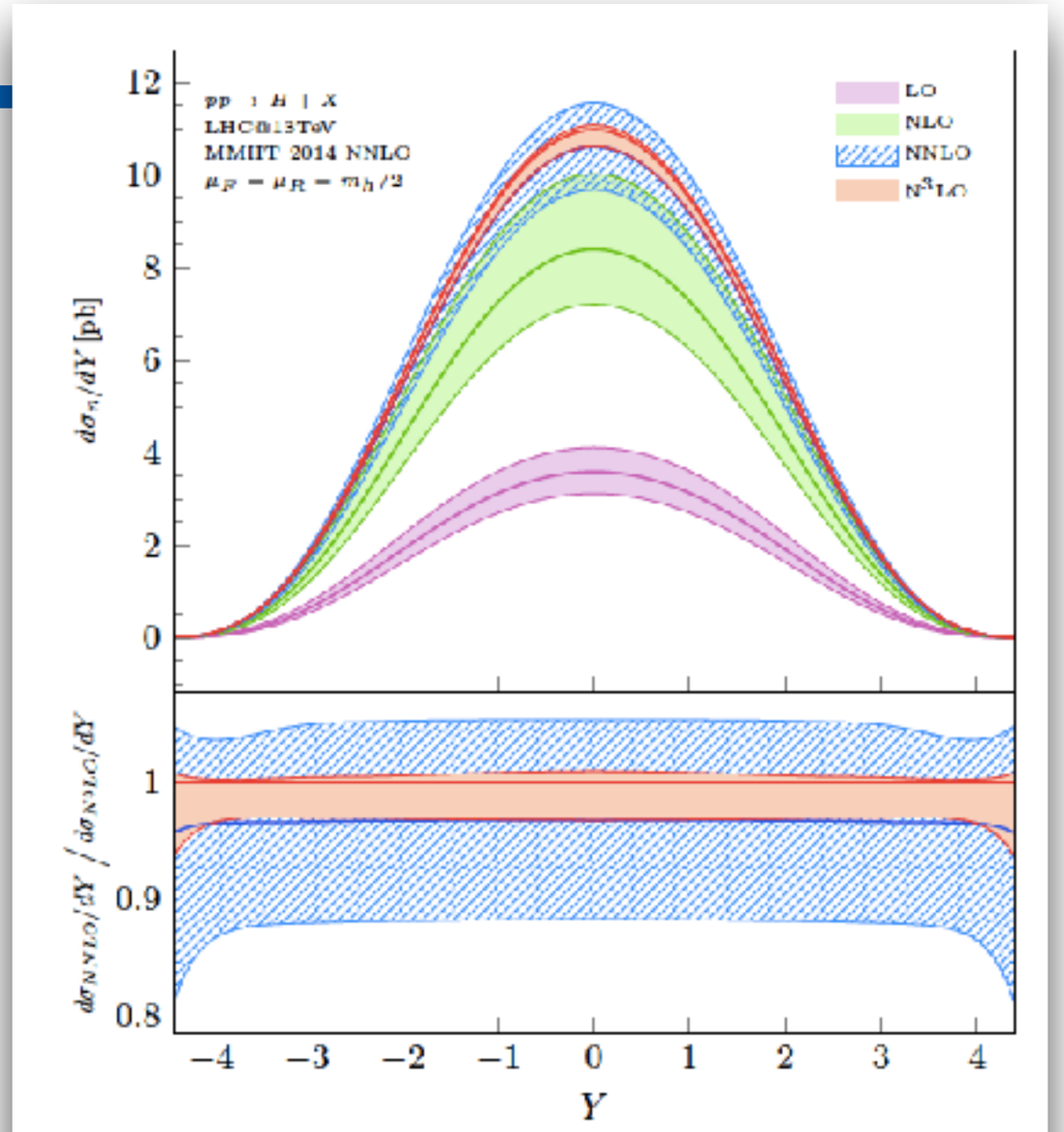
Distributions

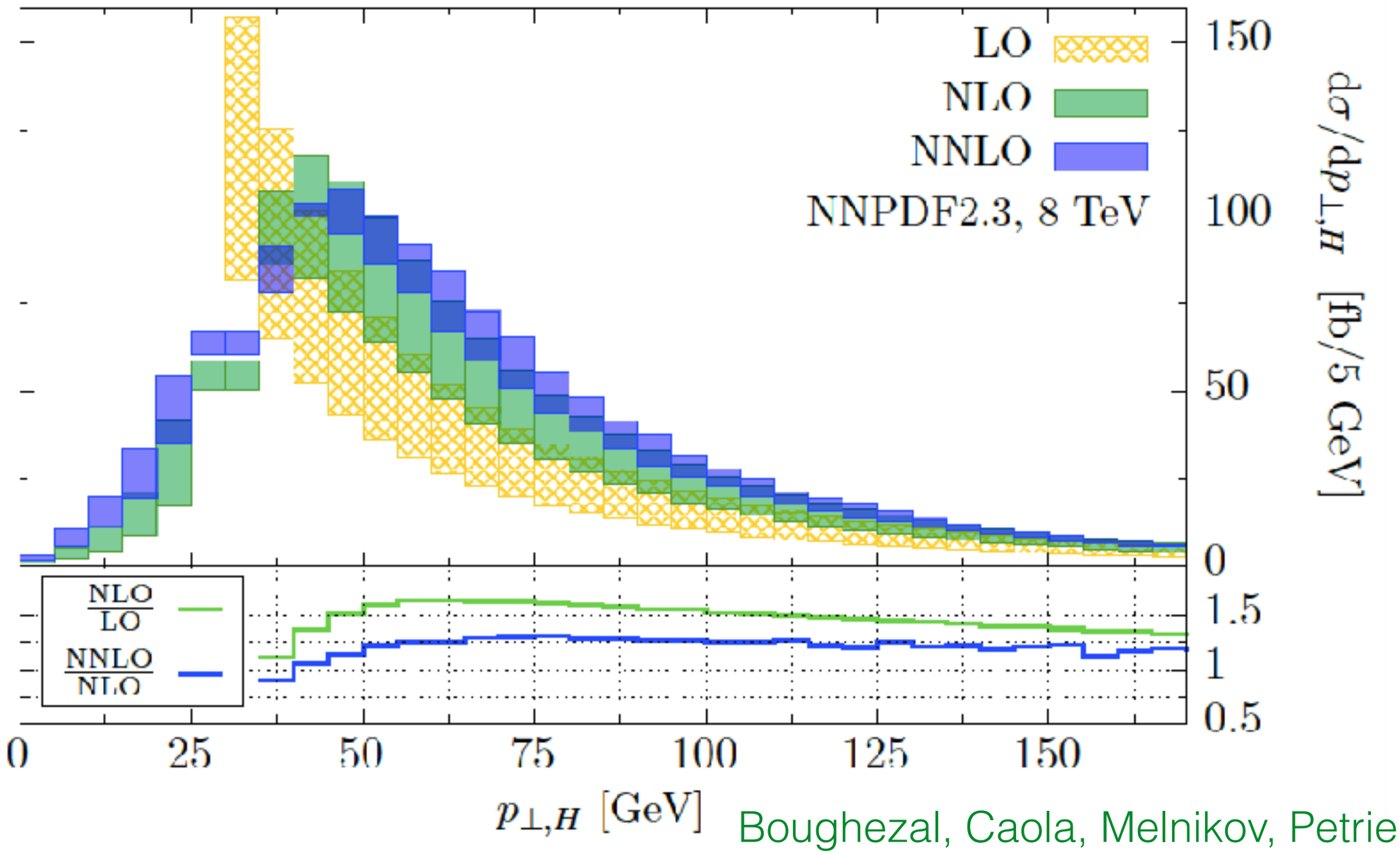




Dulat, Mistlberger, Pelloni 2018

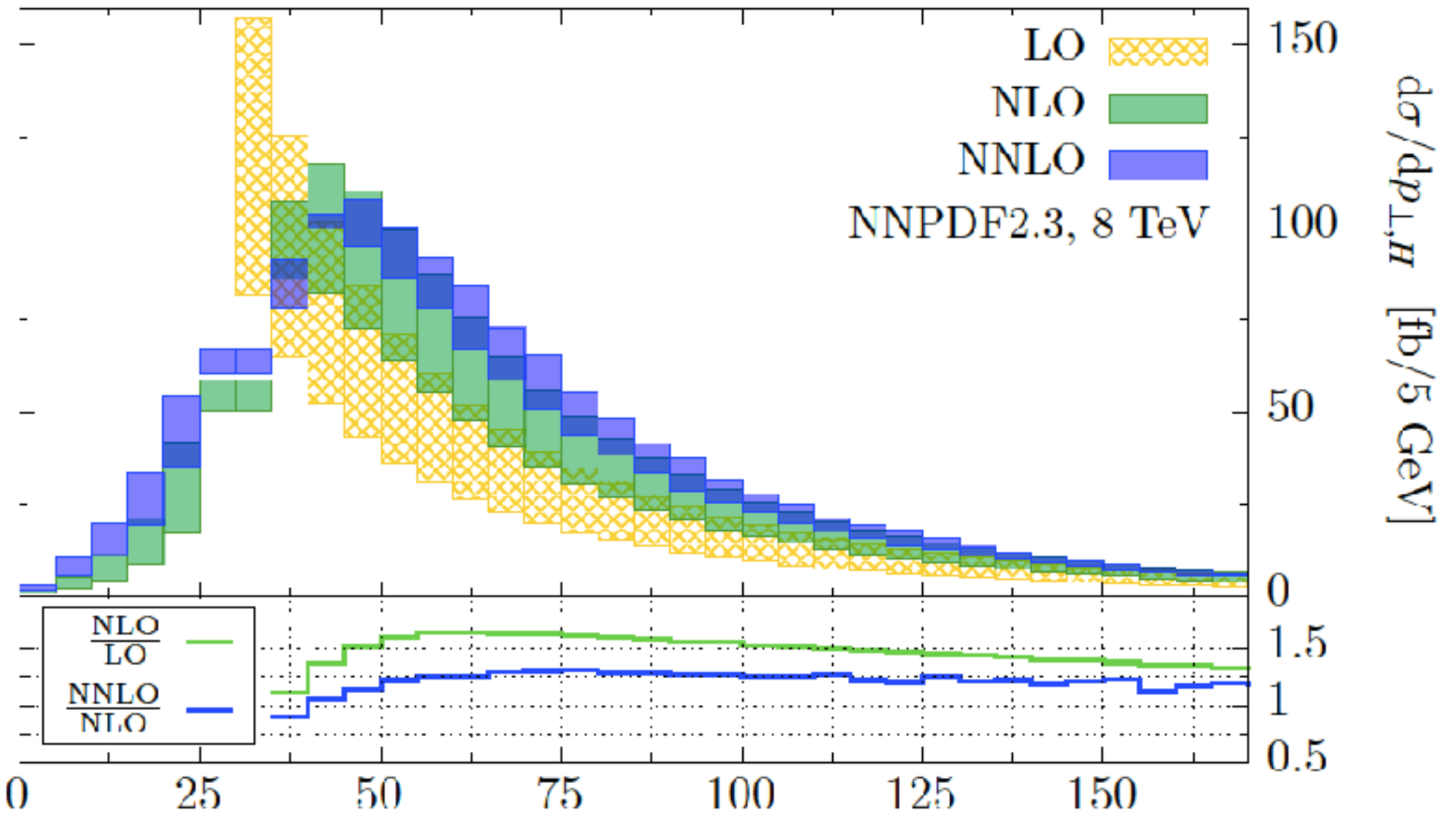
Cieri, Chen, T.
Gehrmann,
Glover, Huss 2018

NNLO p_T



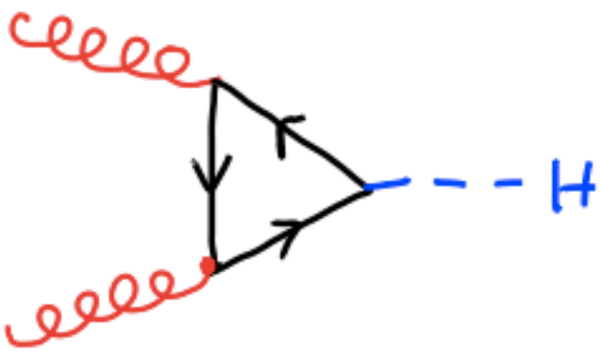
Boughezal, Caola, Melnikov, Petriello, Schulze '13
Chen, T. Gehrmann, Glover, Jaquier '14
Boughezal, Focke, Giele, Liu, Petriello '15

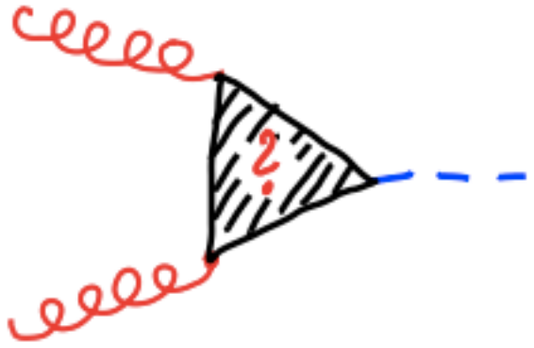
NNLO p_T



Boughezal, Caola, Melnikov, Petriello, Schulze '13
Chen, T. Gehrmann, Glover, Jaquier '14
Boughezal, Focke, Giele, Liu, Petriello '15

Higgs as a probe





$$\sqrt{\hat{s}} = M_H$$

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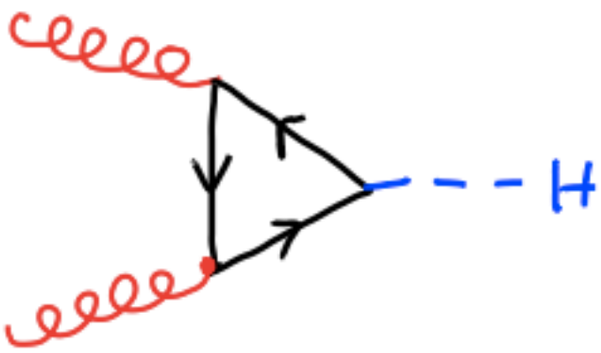
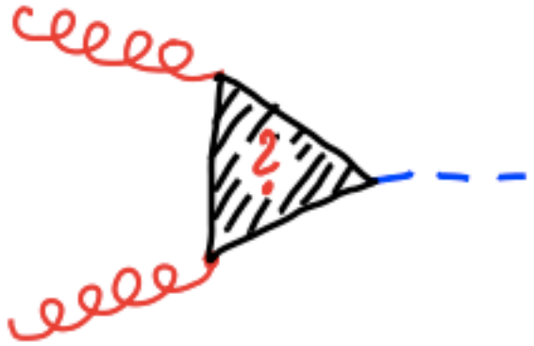
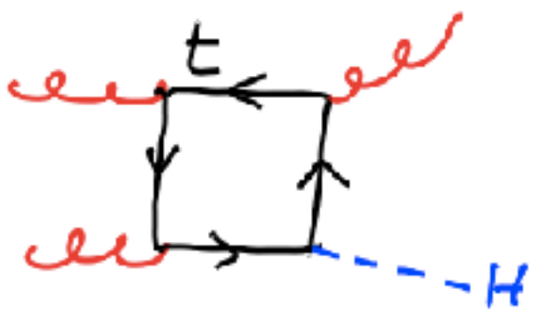
Higgs as a probe





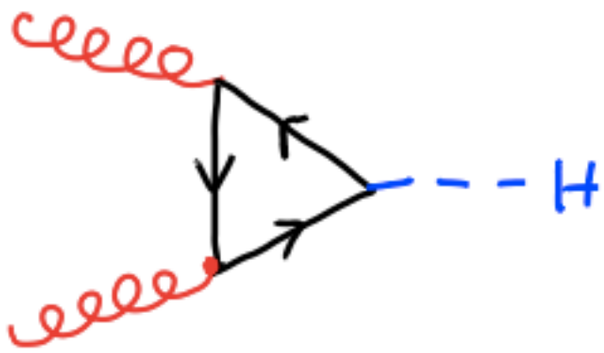
$$\sqrt{\hat{s}} = M_H$$

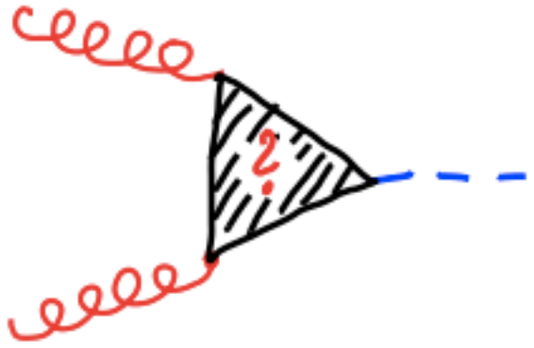


$$\sqrt{\hat{s}} \sim p_T + M_H$$

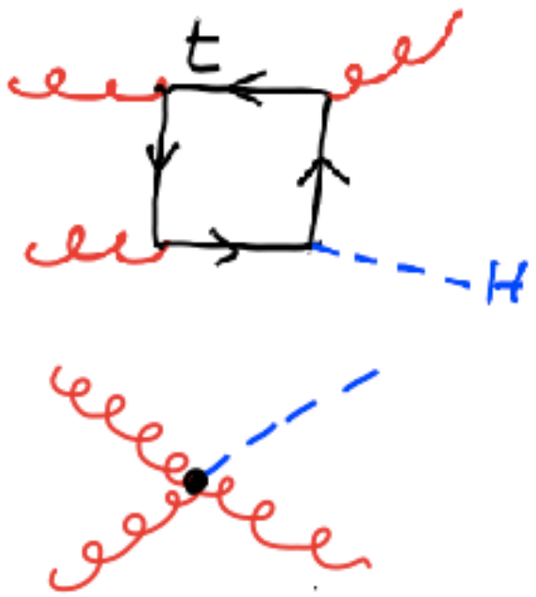
$$m_t \to \infty ?$$

Higgs as a probe





$$\sqrt{\hat{s}} = M_H$$



$$\sqrt{\hat{s}} \sim p_T + M_H$$

$$m_t \to \infty ?$$

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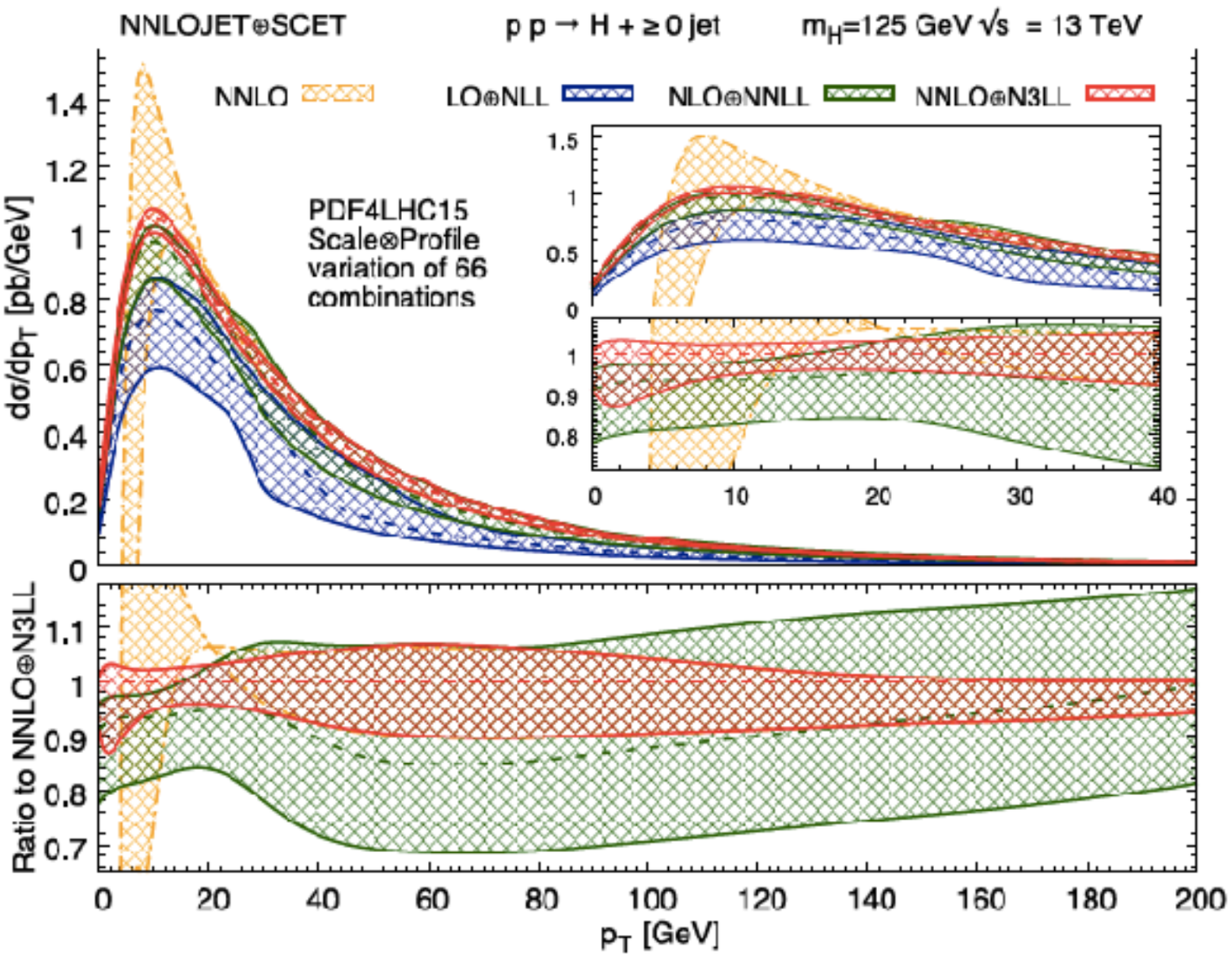
Small-p_T resummation



NNLO⊕N^{3}LL

Chen *et al.* 2018

Bizoń, Monni, Re, Rottoli, Torielli 2017

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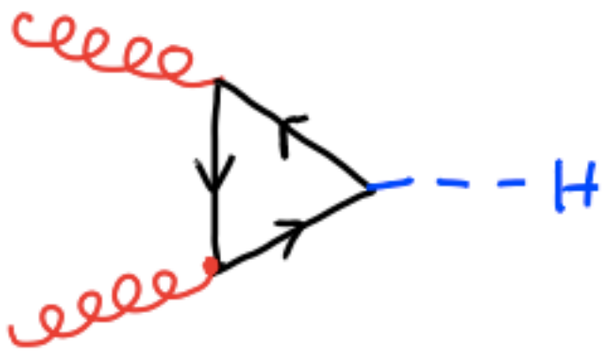
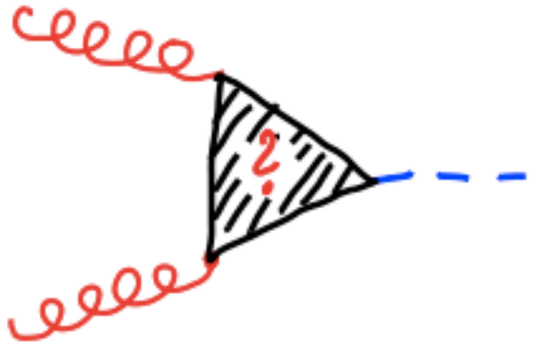
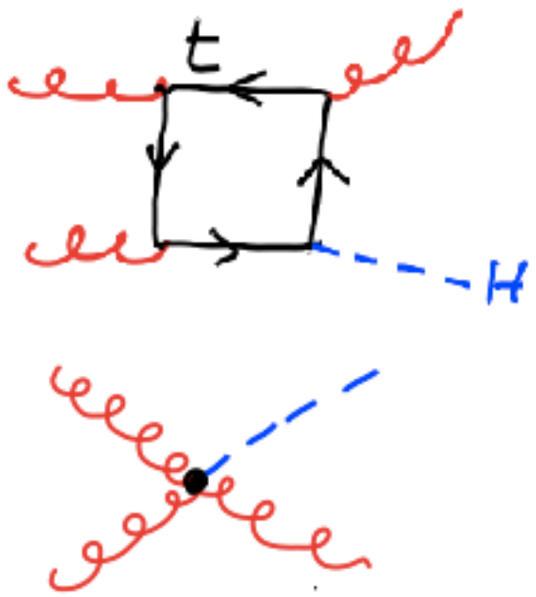
Higgs as a probe





$$\sqrt{\hat{s}} = M_H$$



$$\sqrt{\hat{s}} \sim p_T + M_H$$

$$m_t \to \infty ?$$

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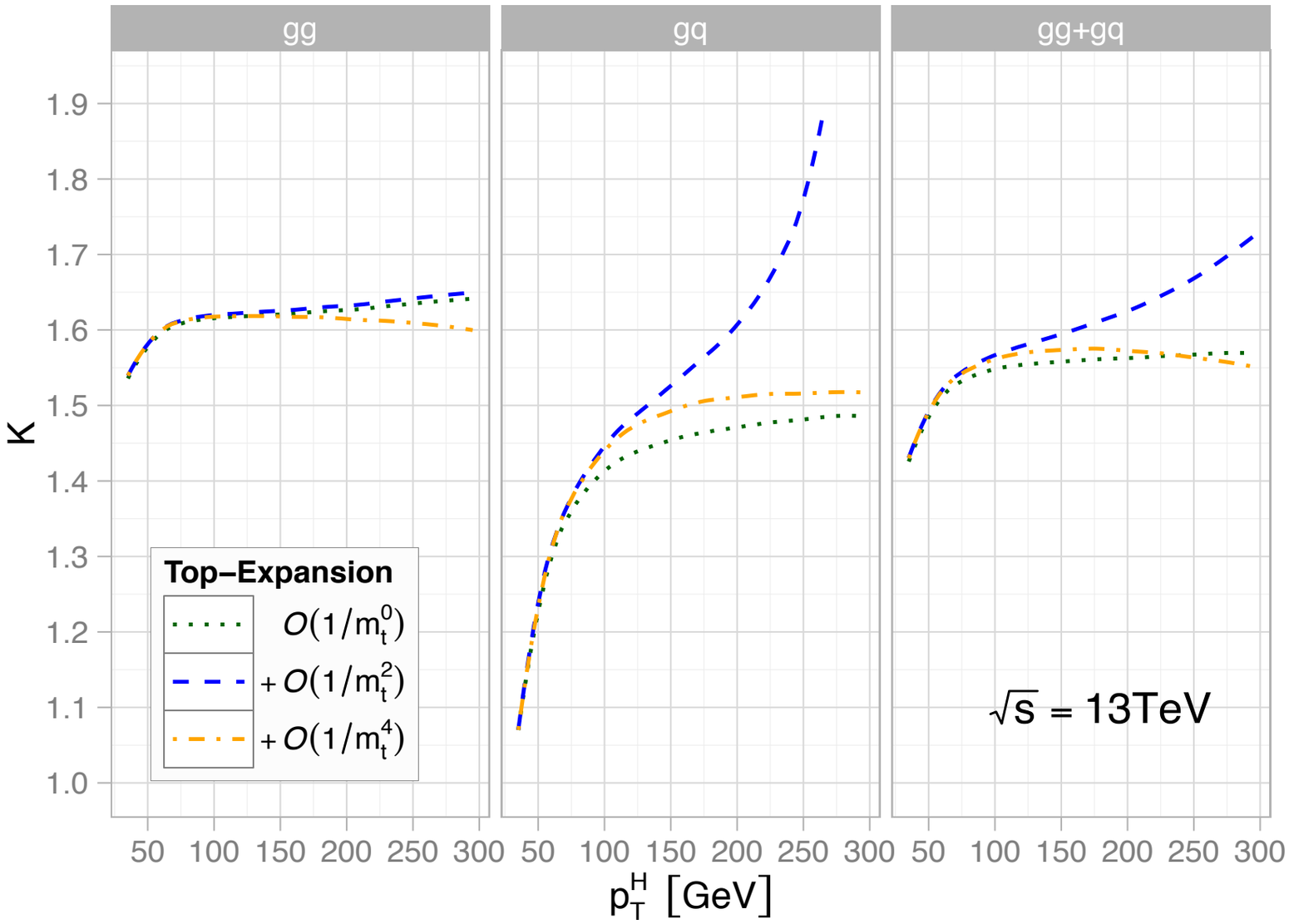
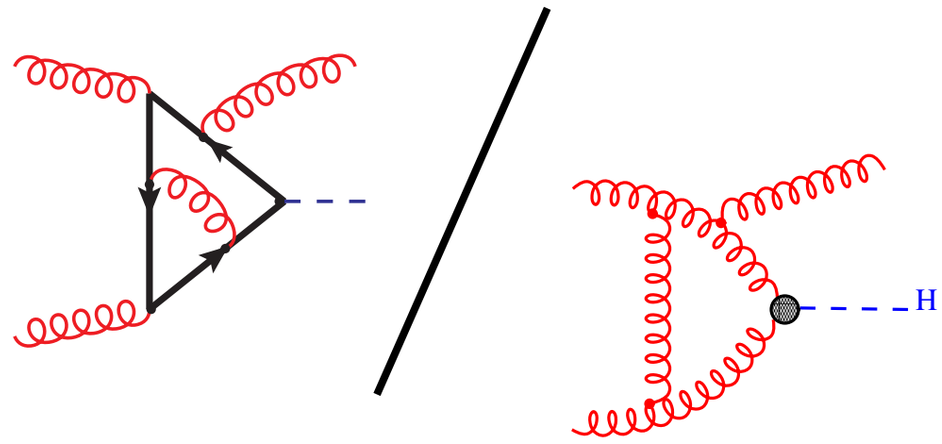
$1/m_t$ expansion



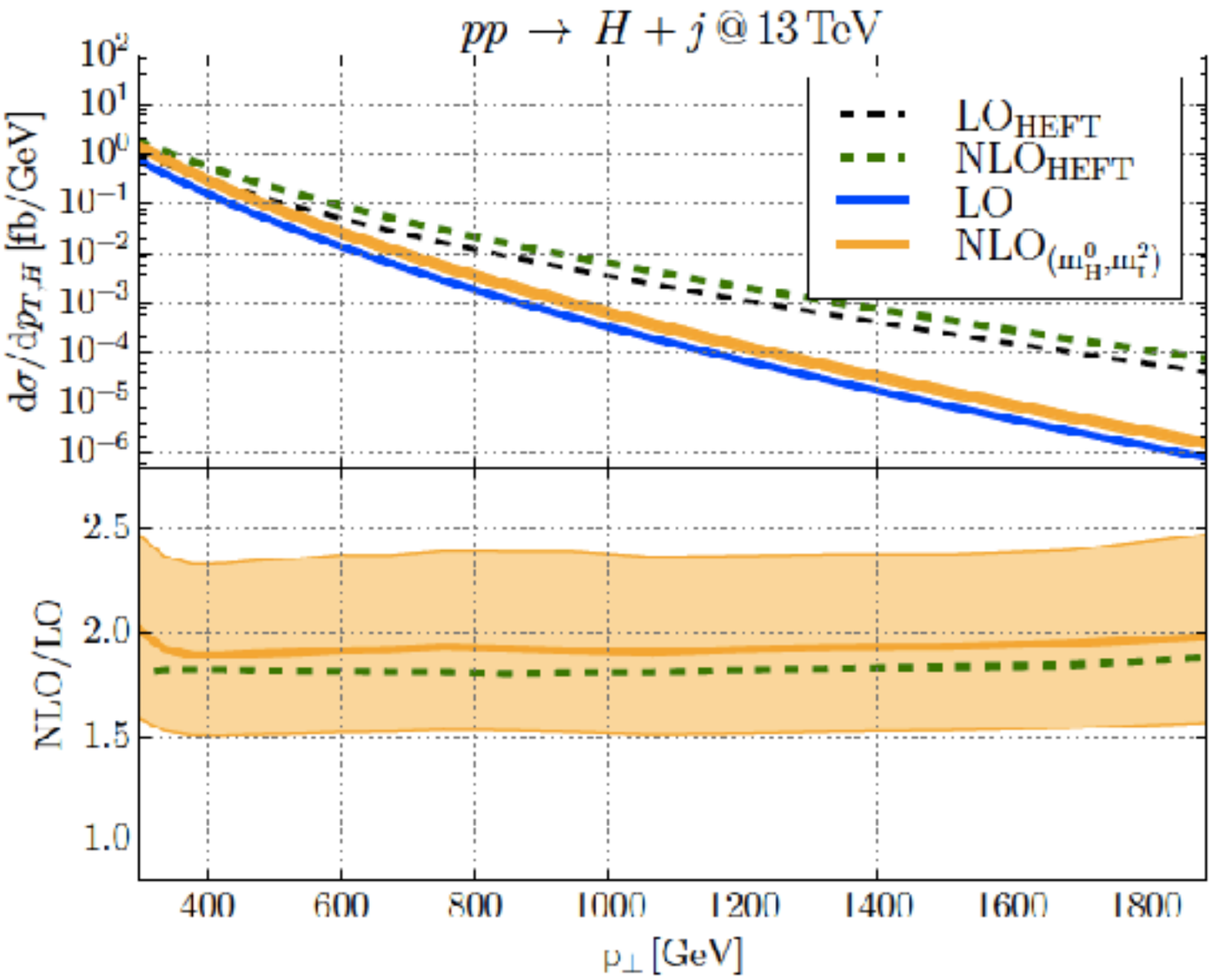


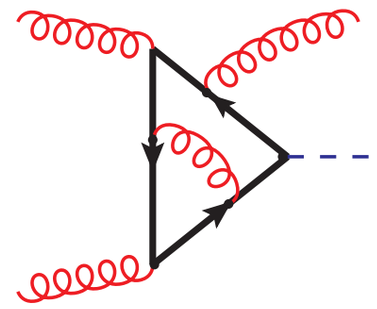
RH, Neumann, Ozeren, Wiesemann ’12

Neumann, Wiesemann ’14

Neumann, Williams ’17

Large p_T



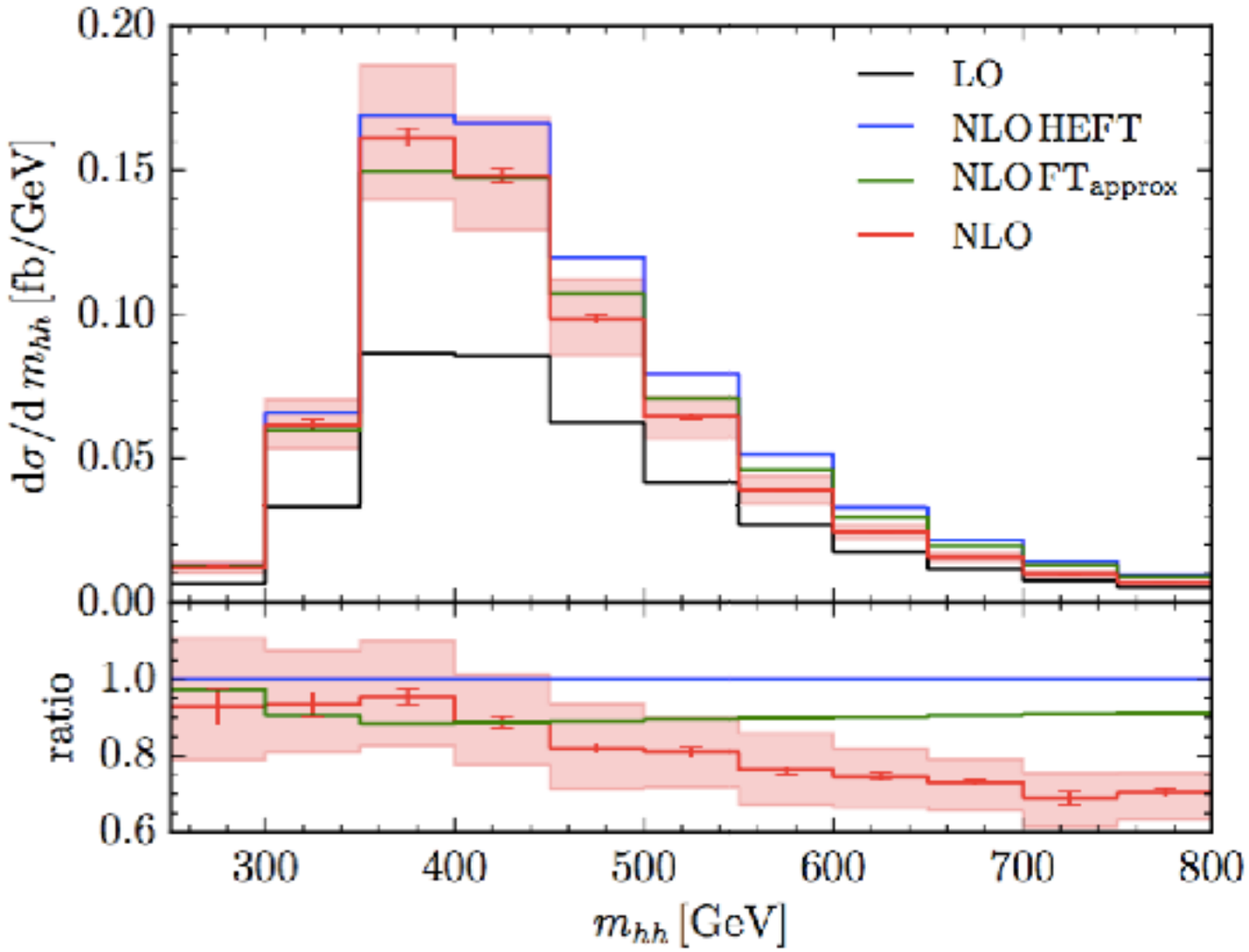


$$p_\perp \gg m_t, M_h$$

Lindert, Kudashkin, Melnikov, Wever 2018

exact m_t dependence: S.P. Jones, Kerner, Luisoni 2018

NLO HH with top mass



Borowka, Greiner, Heinrich, Jones, Kerner, Schlenk, Schubert, Zirke '16
Baglio, Campanario, Glaus, Mühlleitner, Spira, Streicher '18

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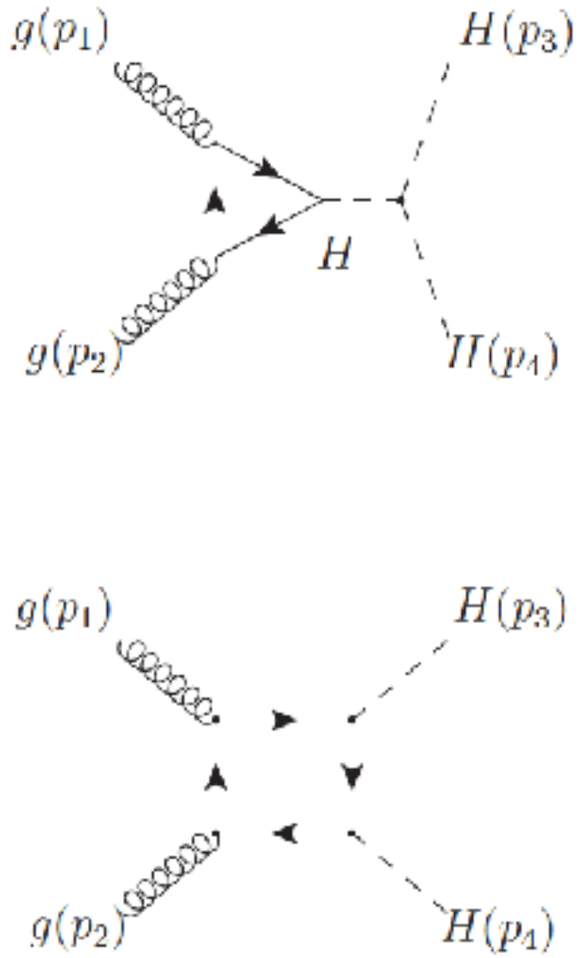
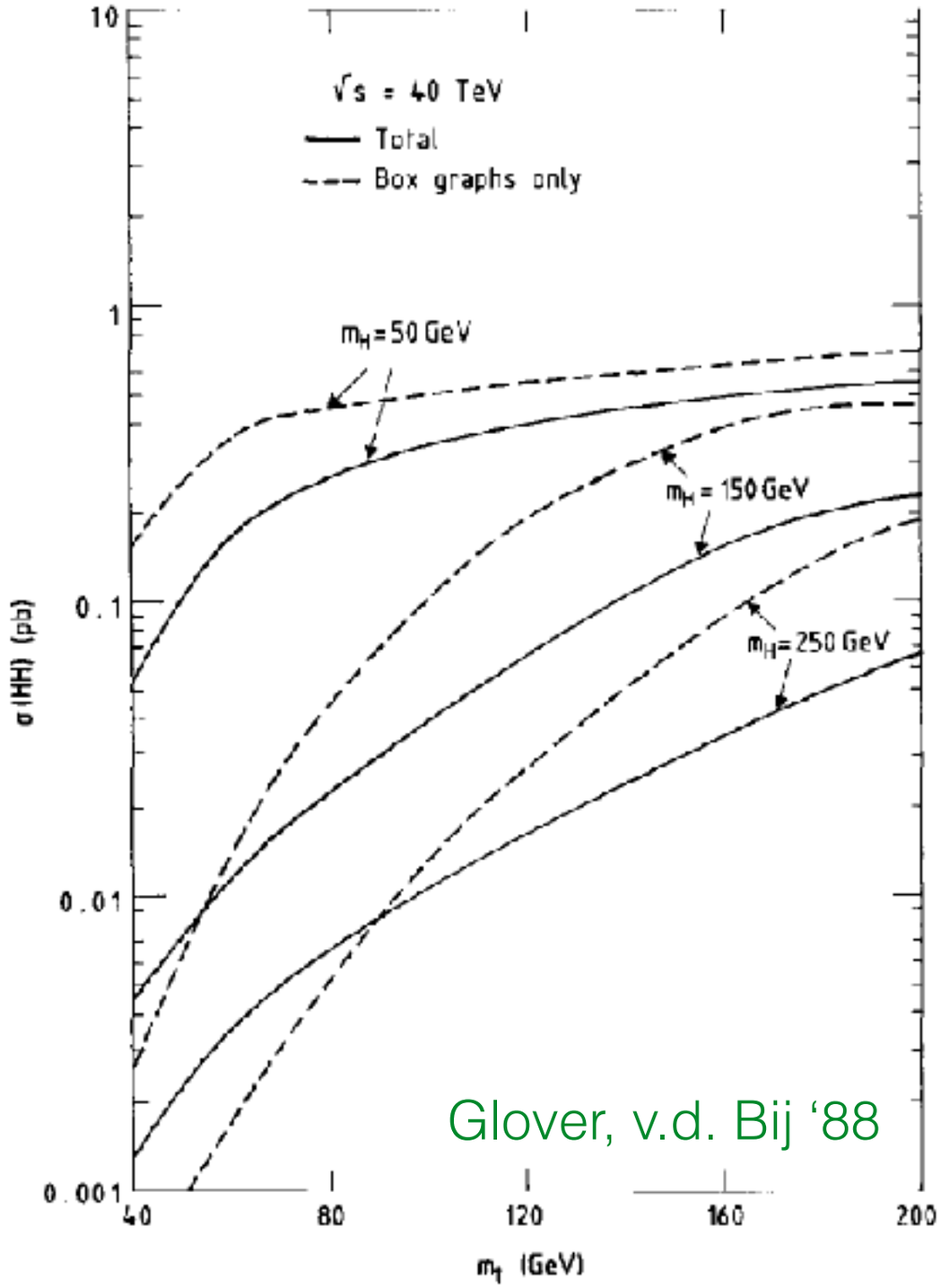
Box-triangle interference





Glover, v.d. Bij '88

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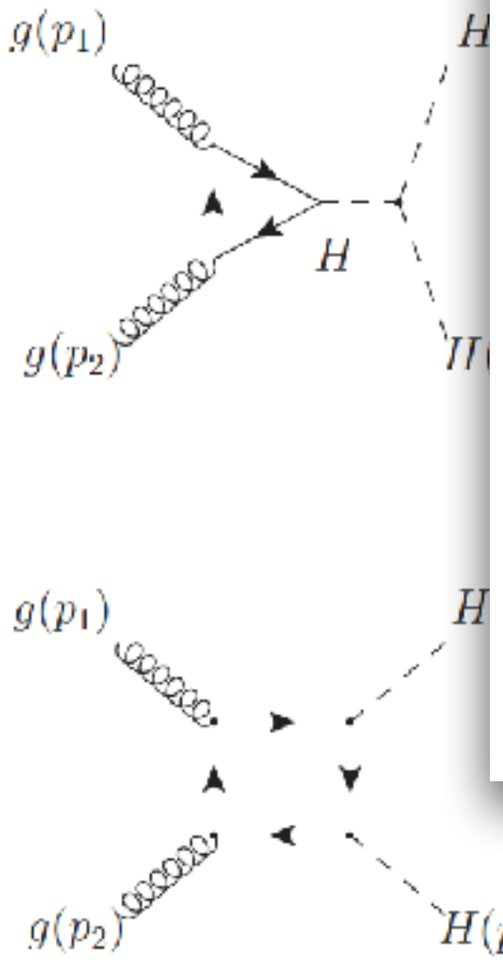
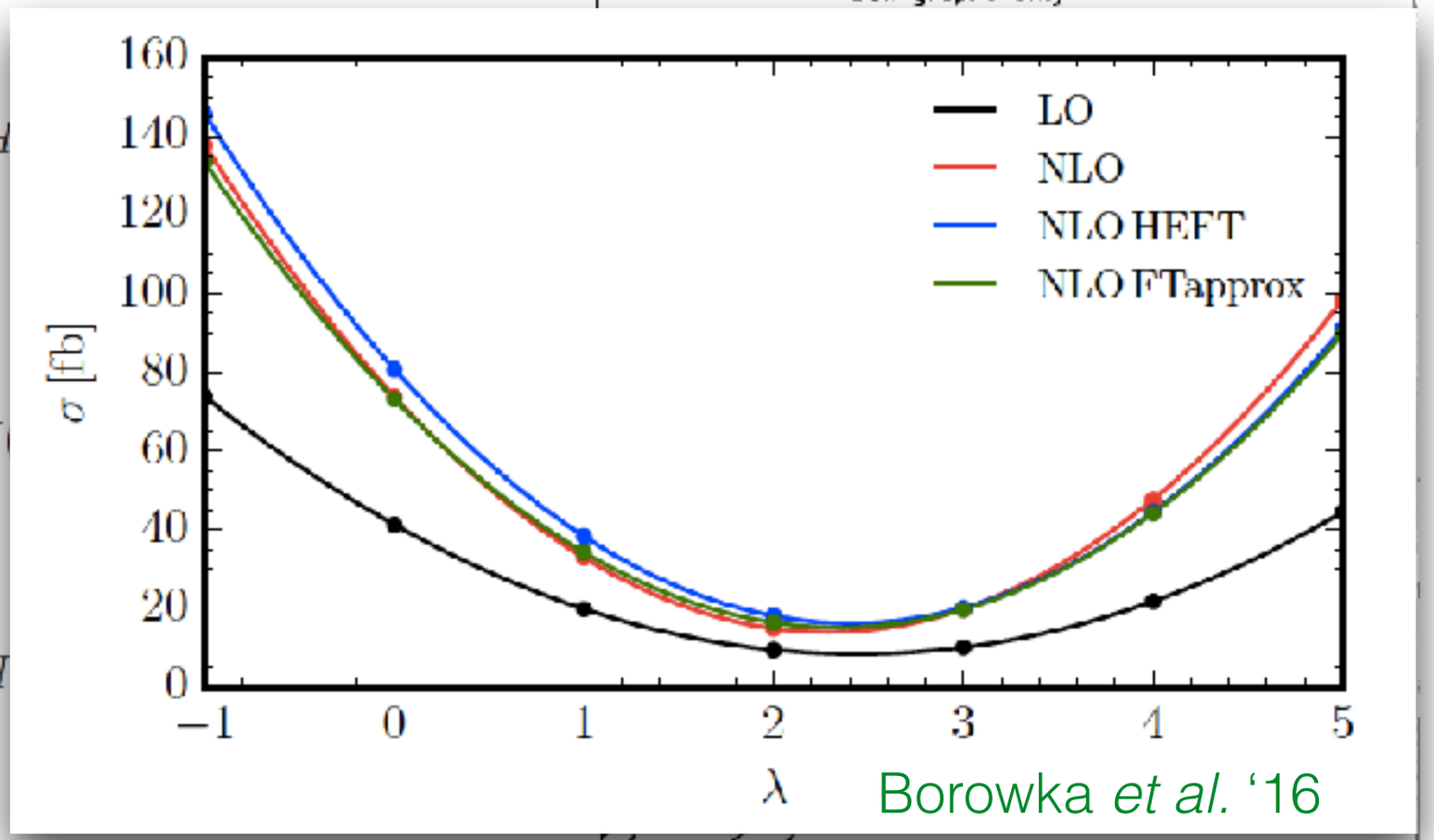
Box-triangle interference

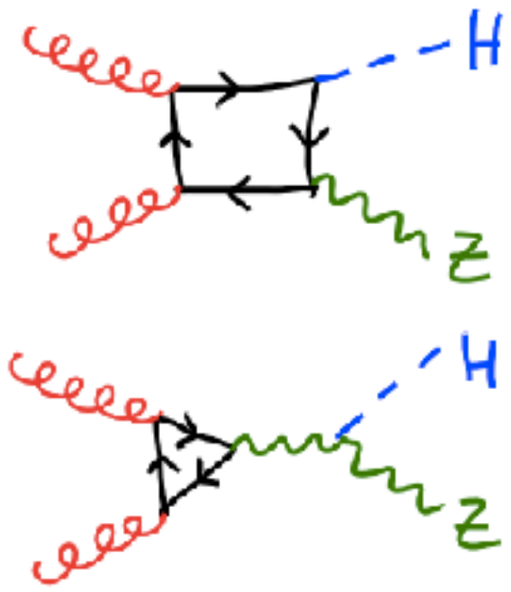


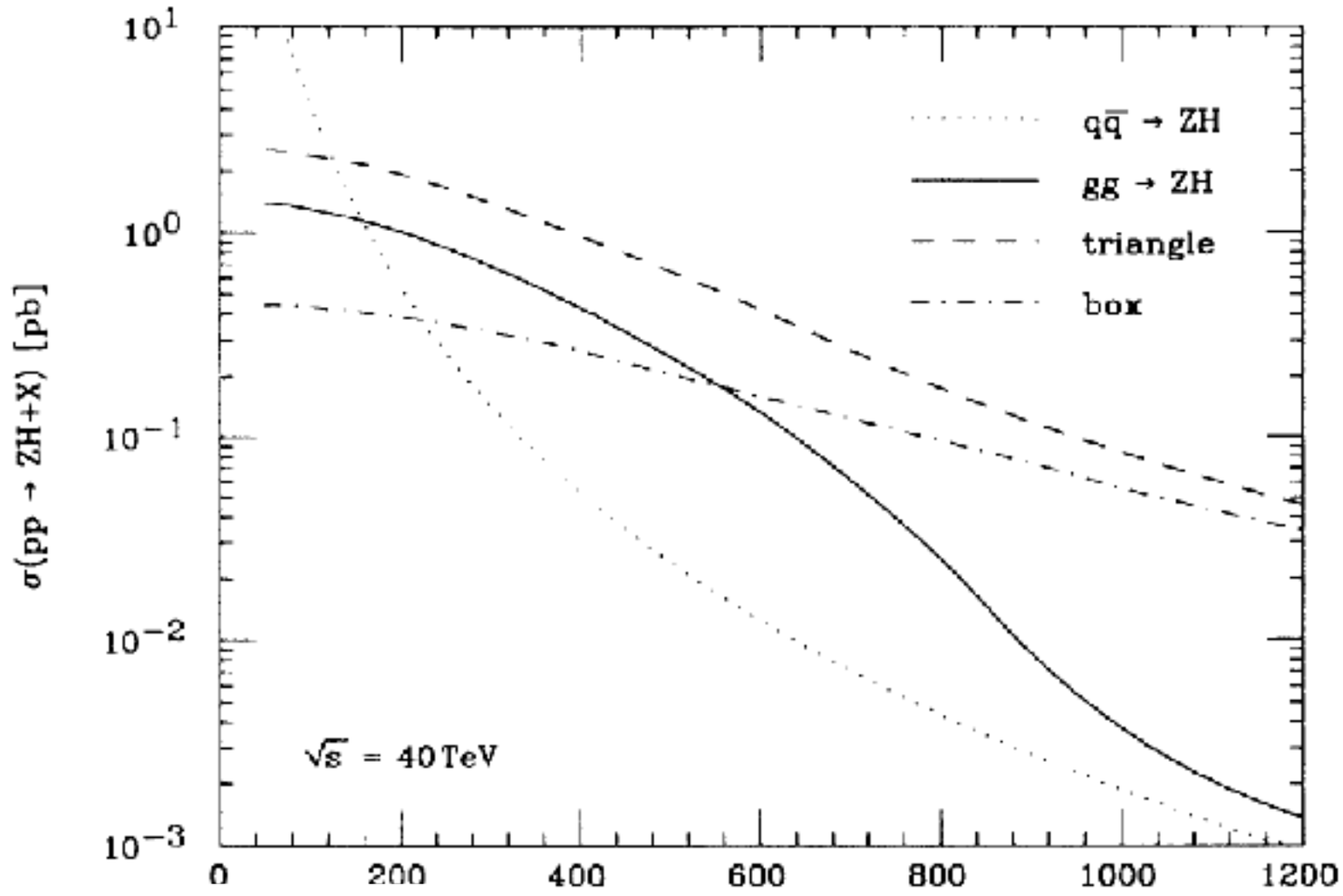


Borowka *et al.* '16

Glover, v.d. Bij '88

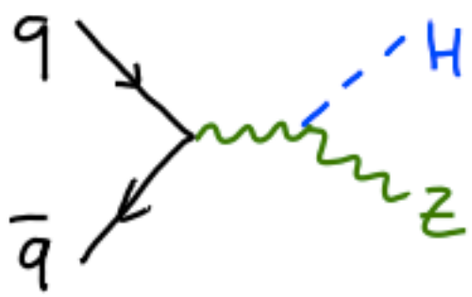
WH/ZH production



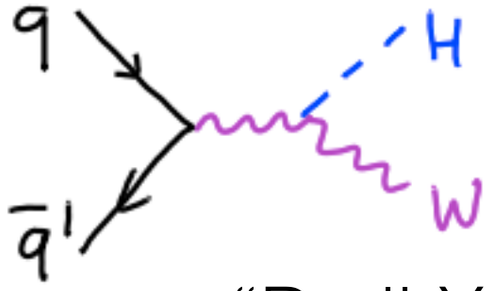


Kniehl ‘91

dominant:



“=“



“Drell-Yan-like”

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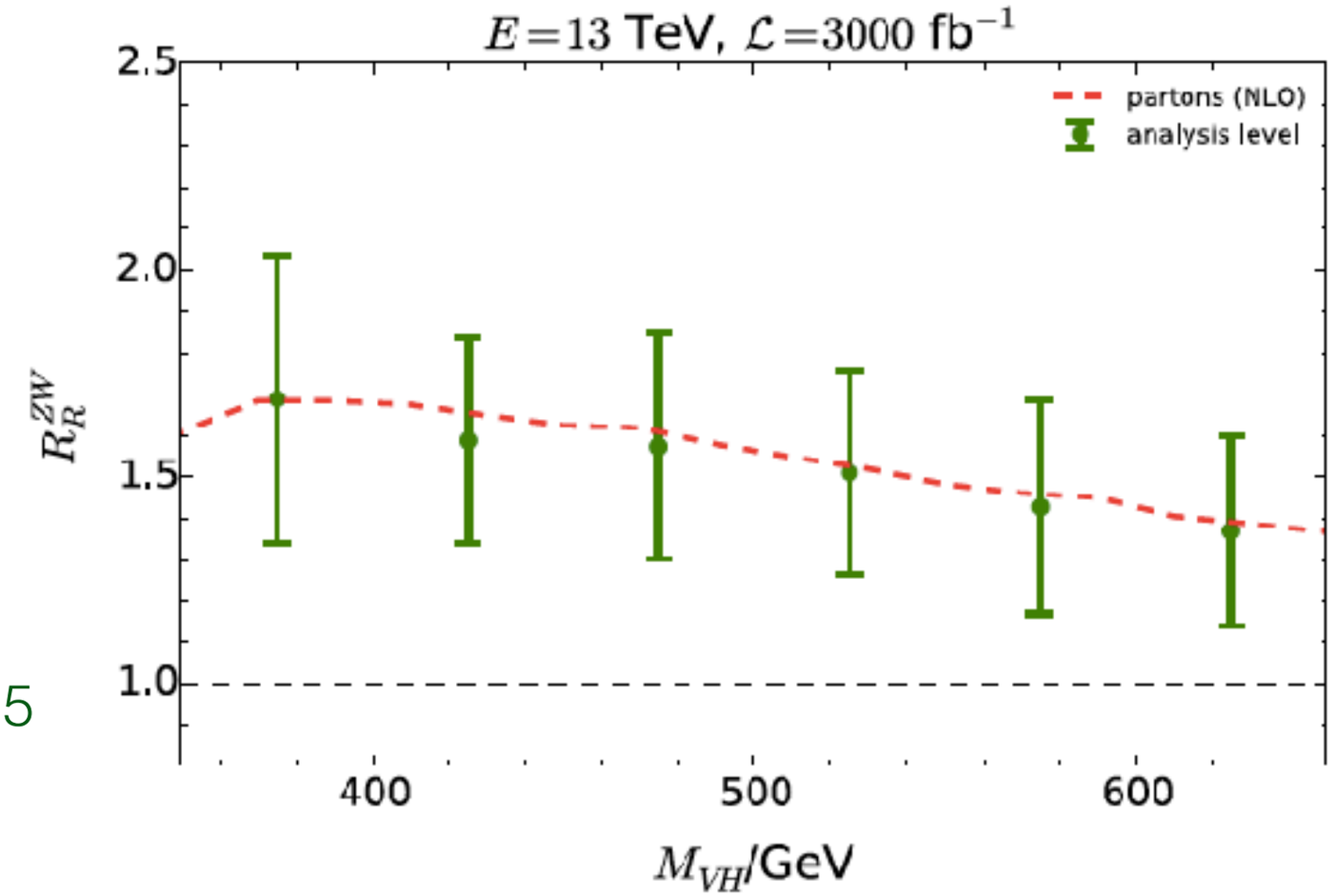
WH/ZH production

Consider ratio:

$$\frac{\sigma_{ZH}}{\sigma_{WH}}$$

“Drell-Yan-like”: NNLO

Caola, Luisoni, Melnikov, Röntsch 2017
Ferrera, Grazzini, Tramontano 2011, 2015



RH, Klappert, Pandini, Papaefstathiou 2018

gg→ZH NLO
heavy top

Altenkamp, Dittmaier, RH, Rzehak, Zirke 2013
Hasselhuhn, Luthe, Steinhauser 2016

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Total cross section

$\sqrt{s}$	σ	δ(theory)	δ(PDF)	$\delta(\alpha_s)$
13 TeV	48.61 pb	$^{+2.08\text{pb}}_{-3.15\text{pb}}$ $\left(^{+4.27\%}_{-6.49\%}\right)$	± 0.89 pb ($\pm 1.85\%$)	$^{+1.24\text{pb}}_{-1.26\text{pb}}$ $\left(^{+2.59\%}_{-2.62\%}\right)$
14 TeV	54.72 pb	$^{+2.35\text{pb}}_{-3.54\text{pb}}$ $\left(^{+4.28\%}_{-6.46\%}\right)$	± 1.00 pb ($\pm 1.85\%$)	$^{+1.40\text{pb}}_{-1.41\text{pb}}$ $\left(^{+2.60\%}_{-2.62\%}\right)$
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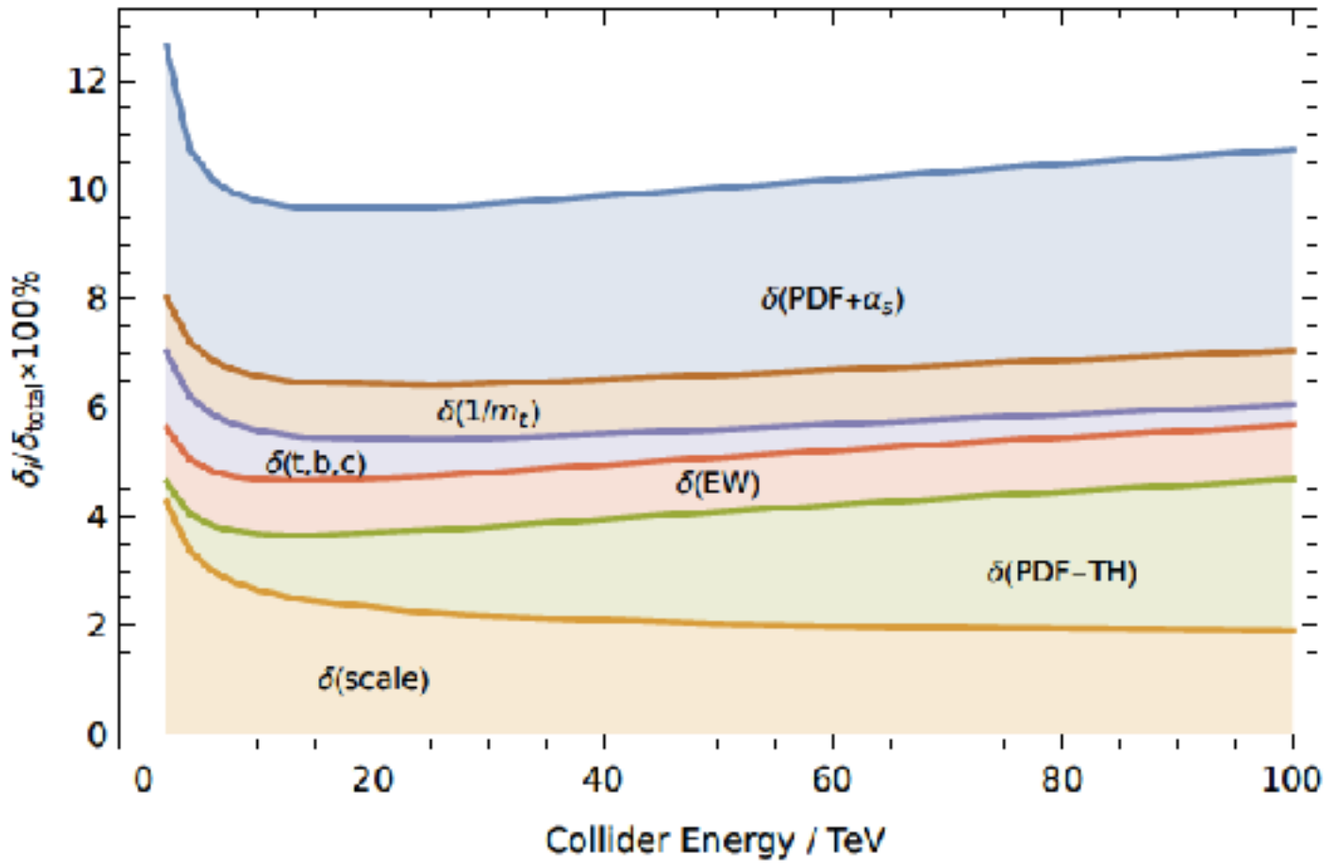

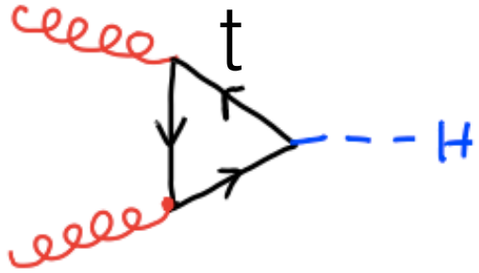

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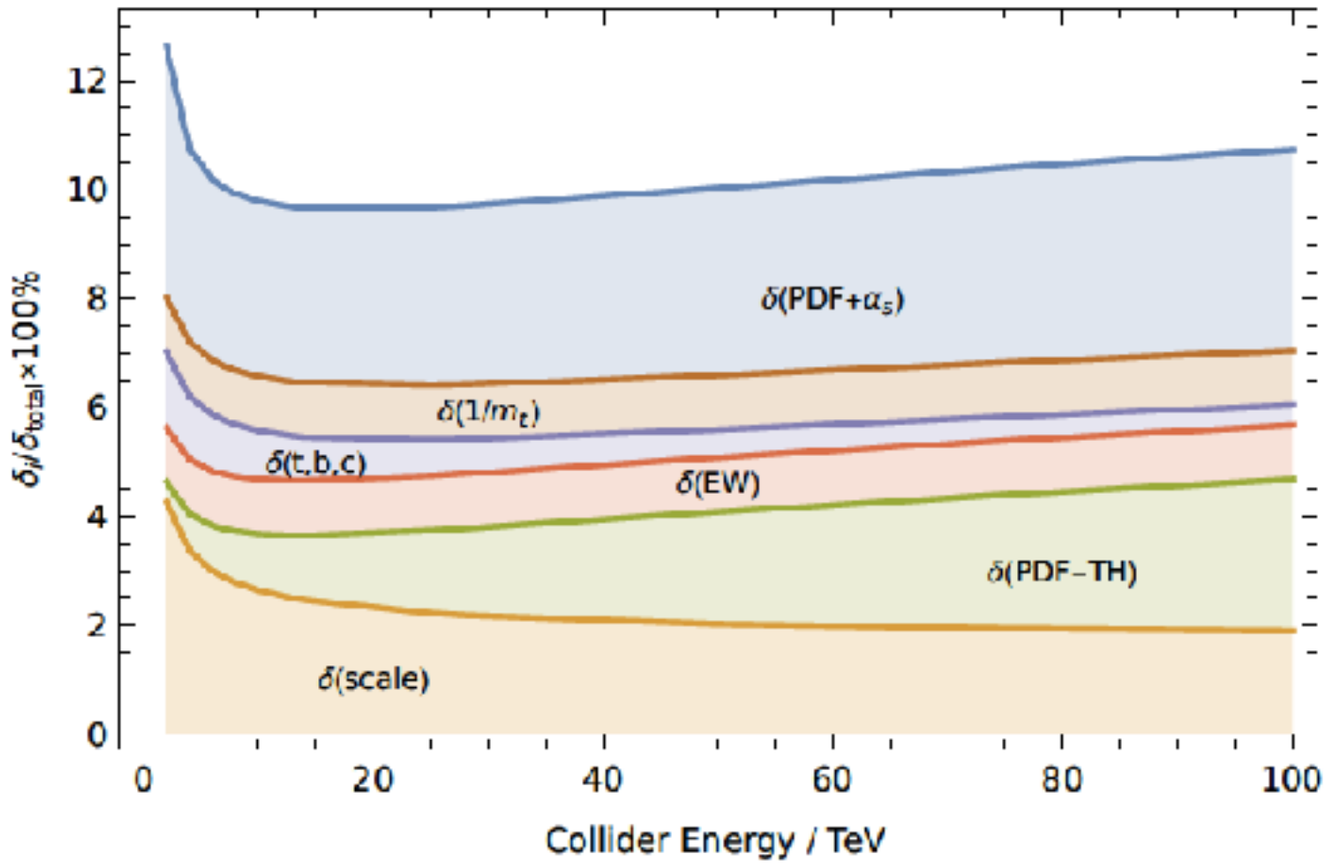

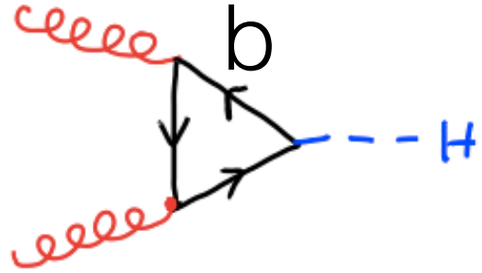

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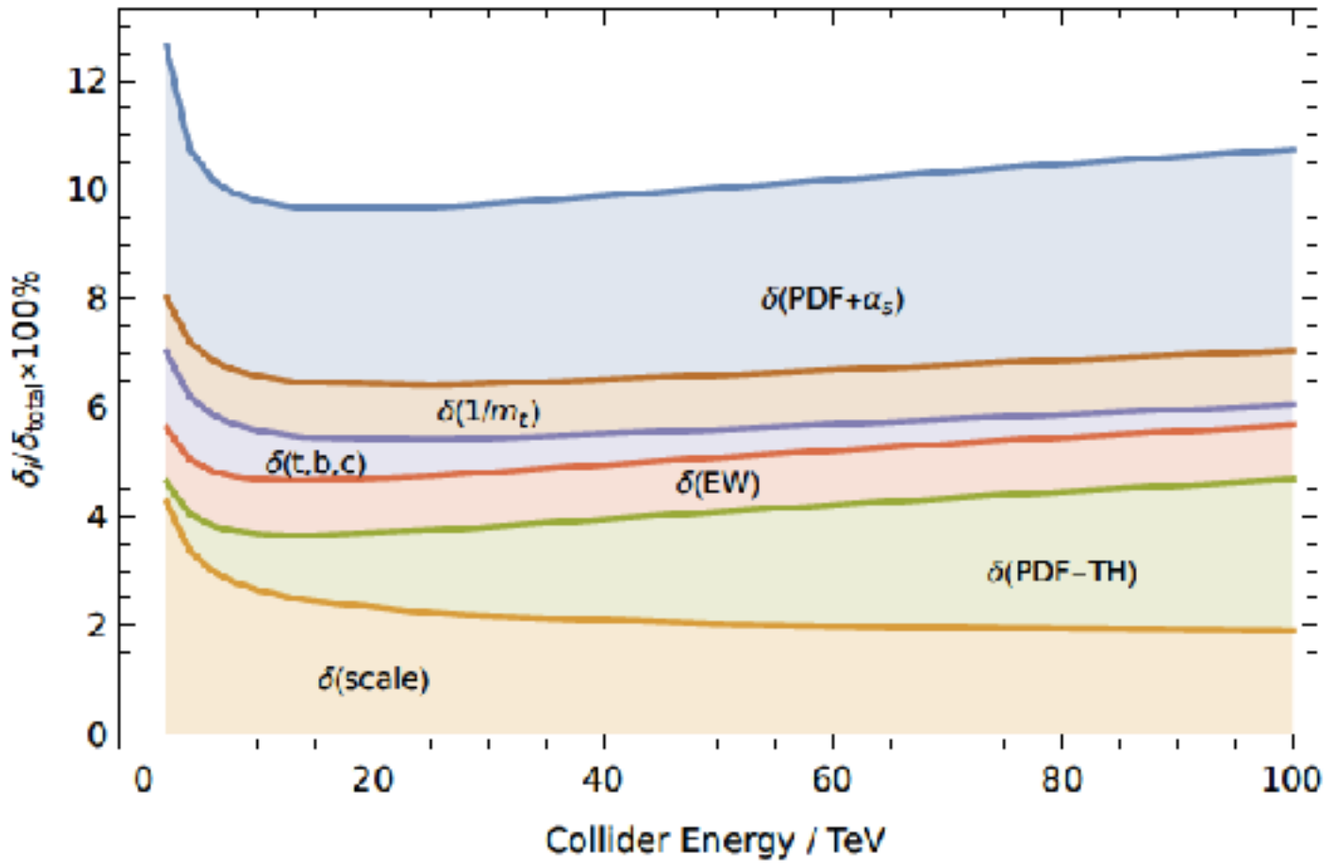

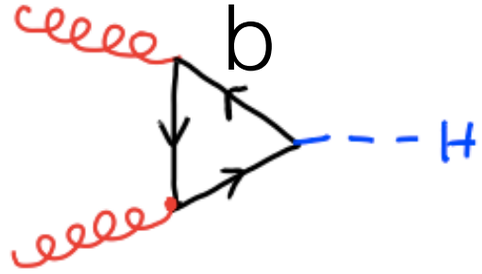

No “heavy-bottom limit”
Only NLO result!

LO: -10%
NLO: -1%

R. Harlander, *SM Higgs precision calculations*, June 2019

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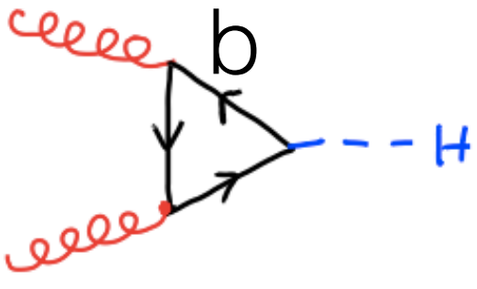
Bottom quark effects



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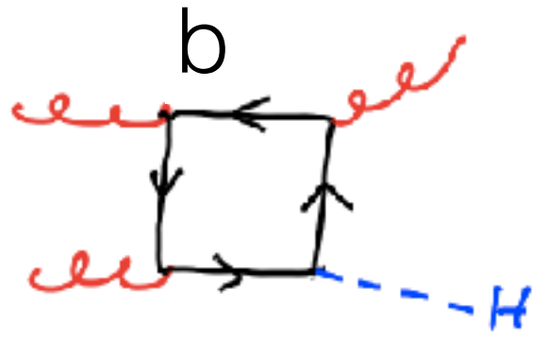

Interference with top:

$$m_b, m_t, M_H, p_T$$

renormalization scale?
resummation scale?

resummation of large logs Melnikov, Penin 2016

NLO p_t top-bottom interference Lindert, Melnikov, Tancredi, Wever 2017

→Napoletano

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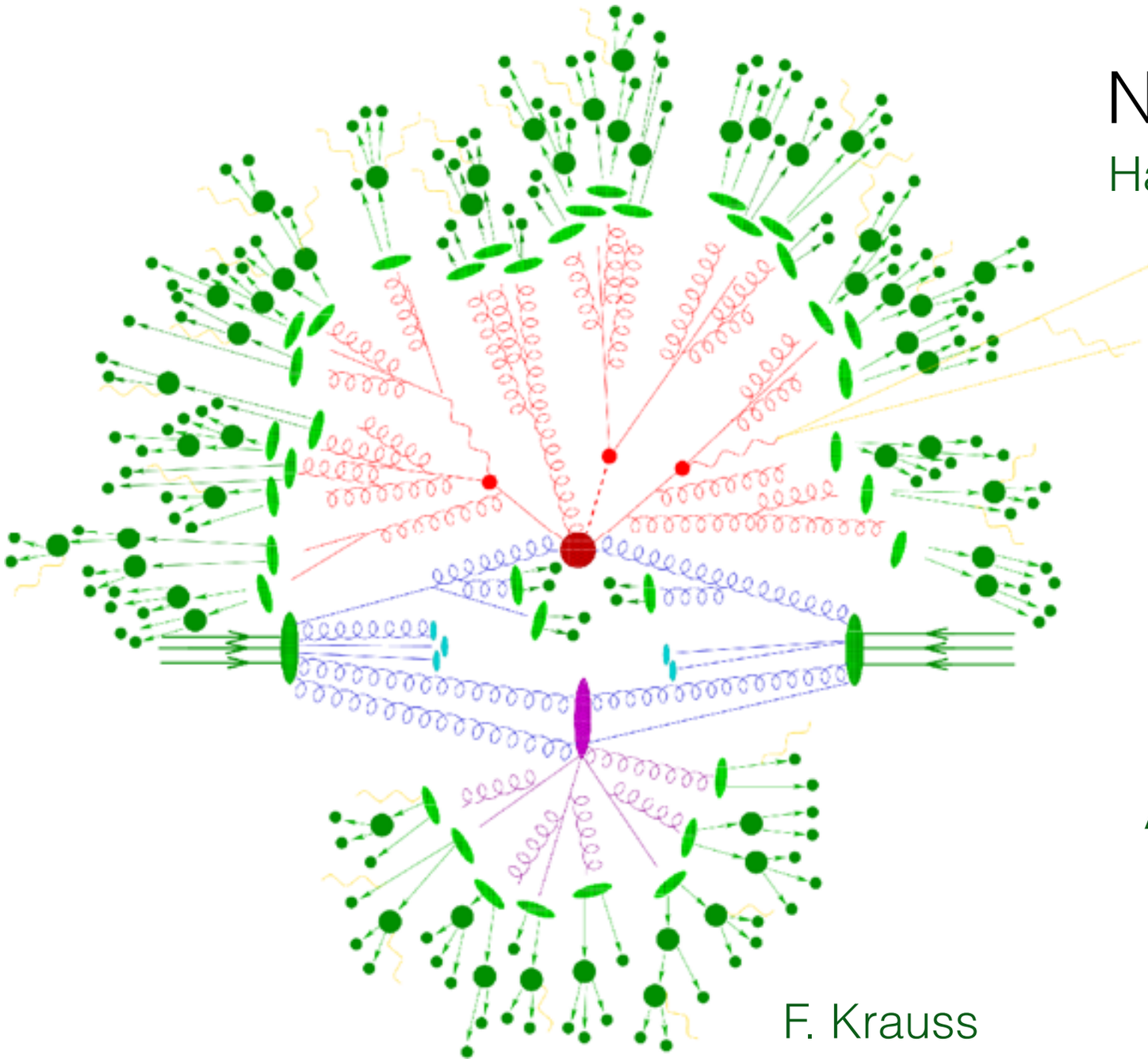
What made all of this possible…

Integration-by-Parts	Chetyrkin, Tkachov 1981
Laporta algorithm	Laporta 2000
Canonical basis	Henn 2013
Sector decomposition	Binoth, Heinrich 2000
NNLO subtraction	Catani, Grazzini 2007 Gehrmann-De Ridder, Gehrmann, Glover ++ 2005ff Czakon 2010 Boughezal, Melnikov, Petriello 2012 Paola, Melnikov, Röntsch 2017 Stuart, Tackmann, Waalewijn 2010 Boughezal, Liu, Petriello 2015 Cacciari, Dreyer, Karlberg, Salam, Zanderighi 2015

Things I skipped…



F. Krauss

NNLO ⊗ PS

Hamilton, Nason, Re, Zanderighi 2013

Alioli, C.W. Bauer, Berggren, Tackmann, Walsh, Zuberi 2014

Höche, Li, Prestel 2014

gg→H with m_t effects

Hamilton, Nason, Zanderighi 2015

WH, ZH

Astill, Bizoń, Re, Zanderighi 2016, 2018

Things I skipped…

VBF: N^{3}LO Dreyer, Karlberg 2018

HH: NLO $\hat{s} \to \infty$ Davies, Mishima, Steinhauser, Wellmann 2018

towards NNLO Davies, Herren, Mishima, Steinhauser 2018
Grigo, Hoff, Steinhauser 2015
De Florian, Mazzitelli 2015, 2018
De Florian, Grazzini, Hanga, Kallweit, Lindert, Meierhöfer, Mazzitelli, Rathlev 2016

Approximation methods Xu, Yang 2019
Borowka, Gehrmann, Hulme 2018

Analytic calculations Frellesvig, Bonciani, Del Duca, Moriello, Henn, Smirnov 2018
Badger, Chicherin, Gehrmann, Heinrich, Henn, Peraro, Wasser, Zhang, Zola 2019
Chaubey, Weinzierl 2019
…

… and much more!

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Things I skipped…

Decays…

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Conclusions

Enormous progress within the last 10-20 years
NLO: fully automated
NNLO: state of the art
First N^{3}LO results
Current challenge: 2-loop multileg

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Conclusions

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Theory will be ready for the next step.

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